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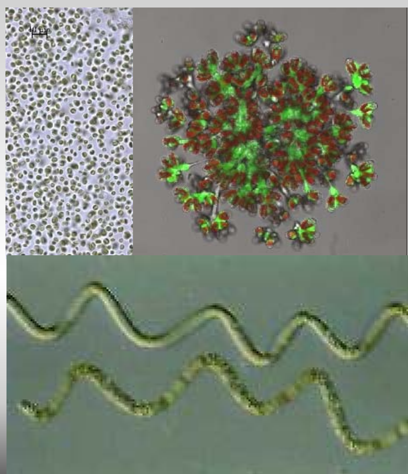
HVP-photobioreactor for intensified microalgal culture: influence of low culture thickness and high biomass concentration on hydrodynamics, gas-liquid mass transfer and biofilm development



$$r_X = \rho\phi A - \mu s \frac{K_r}{K_r + G} X = \rho\phi A - \frac{J_{NADH_2} M_X}{\upsilon_{NADH_2 - X}} \frac{K_r}{K_r + G} X$$

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Outline of the lecture

- Parameters governing PBR performances and intensification principles
- Application for the development of an intensified PBR technology :

  The PRIAM technology
- Hydrodynamics optimisation (two-phase flow in confined geometry)

Parameters governing photobioreactors performances and intensification principles

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Engineering parameters governing PBR performances

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Areal productivities (kg/m² /day or t/ha/year)

$$\langle S_x \rangle_{max} \propto (1 - fd)\ln(1 + \frac{q}{K})$$

$$P_X = \frac{S_X \, S_{light}}{V_R} = S_X a_{light}$$

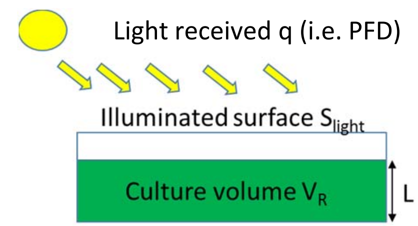
Volumetric productivities (kg/m³/day or kg/m³/year)

$$\langle P_x \rangle_{max} \propto a_{light} \langle S_x \rangle_{max}$$

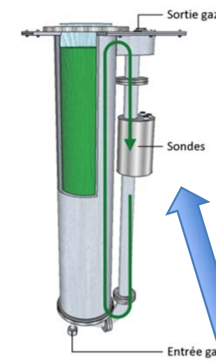
K: Half saturation constant for photosynthesis (biological parameter)

This introduces **3 engineering parameters** that reveal highly influent:

- The collected light as represented by the **Photons Flux Density** (PFD, noted q)
- The **specific illuminated surface** ($a_{light} = S_{light}/V_R = 1/L$ for a flat panel PBR of depth L)
- The non-illuminated volume as represented by the **design dark fraction** f_d (=0 ideally)



$$a_{light} = \frac{S_{light}}{V_R} = \frac{1}{L}$$



Recirculation loop

Culture systems presenting non-illuminated volume (i.e. f_d)

Tank (internal circulating loop)

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More details:

- Pruvost J, Cornet JF. Knowledge models for engineering and optimization of photobioreactors. In: C.Walter CPa, ed. Microalgal Biotechnology: De Gruyter GmbH & Co. KG; 2012:181-224.
- Cornet J-F. Calculation of optimal design and ideal productivities of volumetrically lightened photobioreactors using the constructal approach. Chem. Eng. Sci. 2010;65(2):985-998.

Intensification of PBR performances

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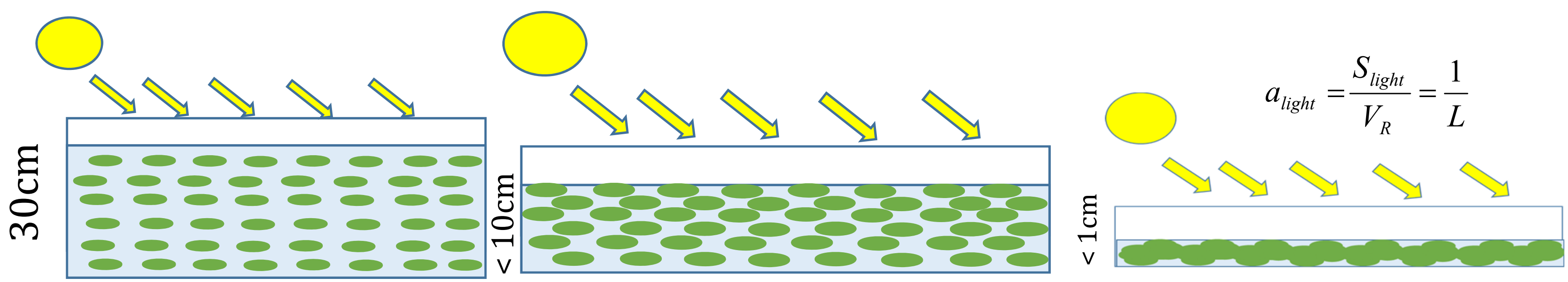
Some guidelines for the design of optimal PBR intensification:

- The design dark fraction (f_d) has to be made **as low as possible** → $f_d \rightarrow 0$
- **Areal productivities are mainly fixed by light received** (q), and increasing light received will increase kinetics performances → q ↗
- **Volumetric productivities can be increased while keeping constant areal productivities** (and limits are from the engineering point of view, as determined by the limit in achievable value of a_{light}) → a_{light} ↗ (L ↘)

Important note: In all cases, the system has to provide sufficient control to reach the light-limited regime (no other limitation than light occurs: no limitation by nutrients or dissolved carbon, near-optimal values of pH and temperature…)

The role of a_{light} introduces the « High Volumetric Productivity » concept



Open systems
$Cx_{max} \approx 0.1\text{-}0.2$ (g/l)

Standard PBR
$Cx_{max} \approx 1\text{-}10$ (g/l)

High-Cell density culture
(High Volumetric Productivity PBR)
$Cx_{max} > 10$ (g/l)

Illustration of the interest of reducing PBR depth

Range of productivities covered by typical culture systems for *A.platensis*

(predicted from engineering formula for same PFD of 250µmole/m²/s)*

Raceway ponds : Depth around 15cm (a_{light}=6.6m^2.m^{-3})

S_x=14.6g/m²/day
P_x=100g/m³/day

Typical Flat panel PBR : Depth of 5cm (a_{light}=20m^2.m^{-3})

S_x=14.6g/m²/day
P_x=290g/m³/day

Thin-film culture systems: Depth <1cm (a_{light}>100m^2.m^{-3})

S_x=14.6g/m²/day
P_x=2900g/m³/day

X30 on volumetric productivity (same production per unit of surface)

Conclusion: Reducing the depth of culture leads to a significant increase in volumetric productivity (proportional to a_{light}, and then 1/L !), and a significant decrease in water needed

Water quantity needed

1. Raceway ponds : 150liters/m^2
2 - Typical PBR : 50liters/m^2
3 – Thin-film culture systems (<10 liters/m^2)

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*Pruvost, J., Cornet, J.F. 2012. Knowledge models for engineering and optimization of photobioreactors. in: Microalgal Biotechnology, (Ed.) C.P.a. C.Walter, De Gruyter GmbH & Co. KG, pp. 181-224.

Application for the development of an intensified PBR technology :

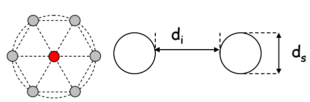
PRIAM technology

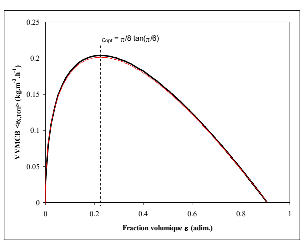
Development of an intensified technology: PRIAM PBR

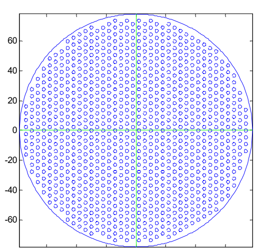
a_{light}: 400 m^2/m_{liq}^3

DiCoFluV PBR
(1 patent)

- *Internal illumination*
- *Optimized by constructal approach*





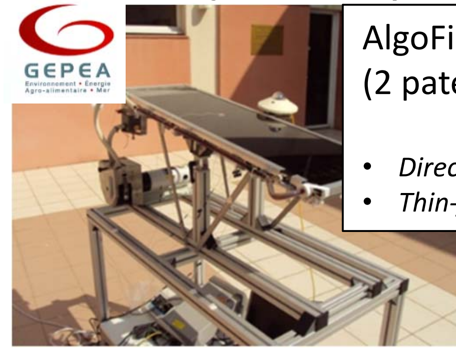


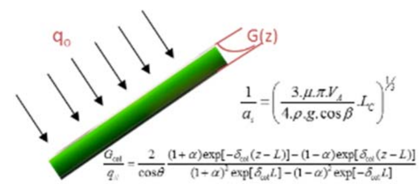
Combination of both concepts for the design of a PBR unit with internal illumination for intensified production of microalgae in artificial light

a_{light} : 470 m^2/m_{liq}^3

AlgoFilm© PBR
(2 patents)

- *Direct illumination*
- *Thin-film concept*





PRIAM Technology

Internal artificial illumination
Thin film culture
Linear scaling of production

Patented technology

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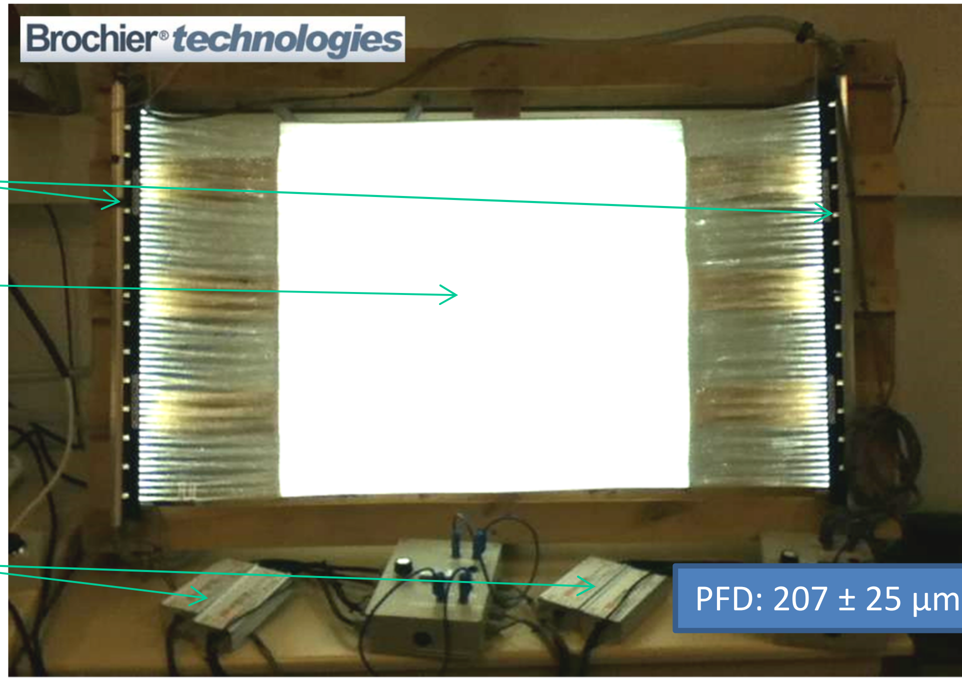
Project funded by the French National Agency (ANR): 234k€
Collaboration with two french companies: Brochier Technologies, AlgoSource Technologie

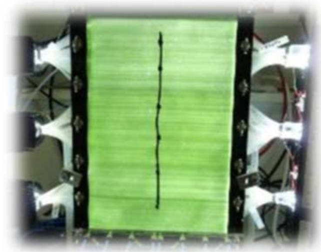
Development of an intensified technology: PRIAM PBR

LEDs sources

Illuminated part

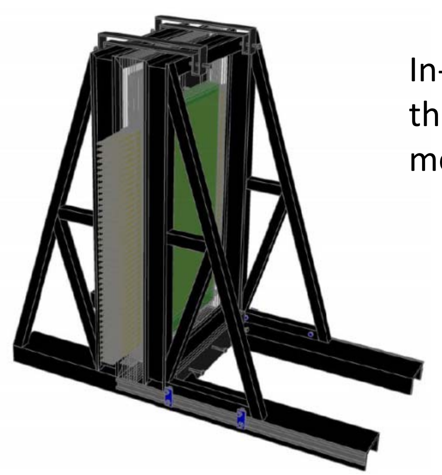
Power units



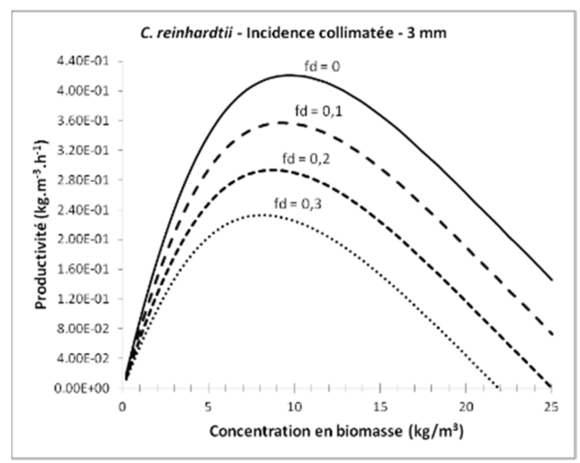


PFD: 207 ± 25 $\mu mol_{h\nu}/(m^2.s)$

Multi-panels assembly for a total volume of $1m^3$ (modular production capacity)



In-silico optimisation through knowledge models



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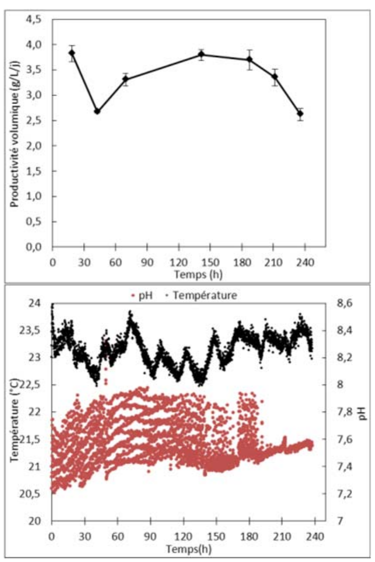
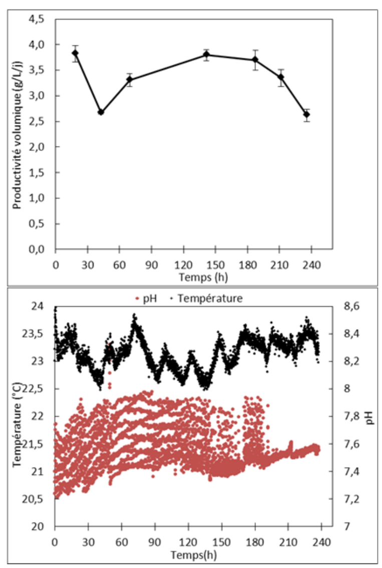
Culture results (*Chlorella vulgaris*)

- Batch culture ($100\mu mol_{h\nu}/m^2/s$): biomass x 6 in 3 days (0.9 to 5.5g/l)
  → *Because of the large growth rate, continuous culture has to be preferred*

- Continuous culture ($200\mu mol_{h\nu}/m^2/s$): biomass productivity of $3.75 kg/m^3/d$ close to the one expected from in-silico modeling ($4kg/m^3/d$, <10% error): breakthrough performance compared to state-of-the-art technologies (x15-30)
  → *Production capacity of 3.5-4kg/day (0.02 for conventional PBR)*

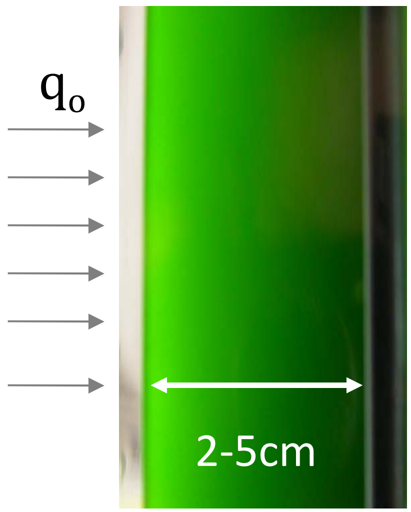
- Biofouling remains moderate, but can be further optimized for long term operation…



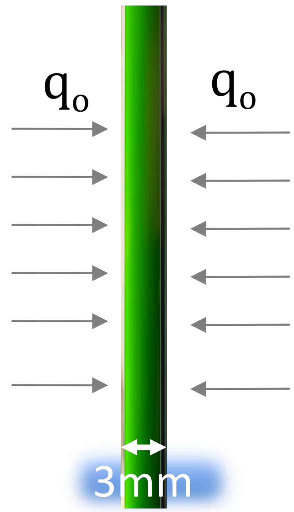


After 2 weeks of culture

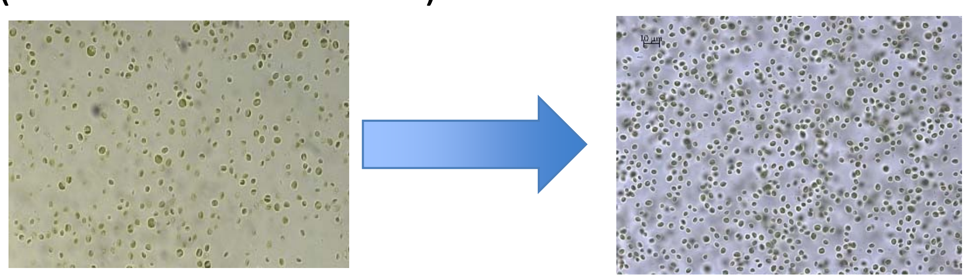
Hydrodynamics: the main limitation to PBR intensification



State-of-the-art technology
(one-side illumination)



PRIAM PBR
(two-side illumination)

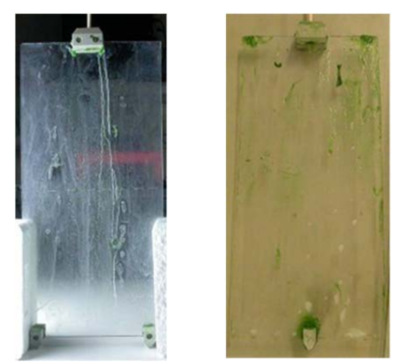


Moving to high-cell density culture
(>10kg/m^3)

Intensified geometry leads to very low culture depth (3mm for PRIAM) with larger biomass concentration

Hydrodynamics becomes the main limiting factor:

- Biofouling of optical surfaces
- Needs to maintain sufficient gas-liquid mass transfer in confined geometry
- Possible change of rheological behavior (shear thinning behavior)



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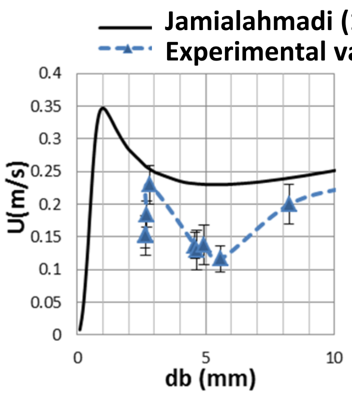
Hydrodynamics optimisation (two-phase flow in confined geometry)

Hydrodynamics in confined geometry (4 mm)

A specific and original hydrodynamics:

- Effect of confinement on terminal velocity :



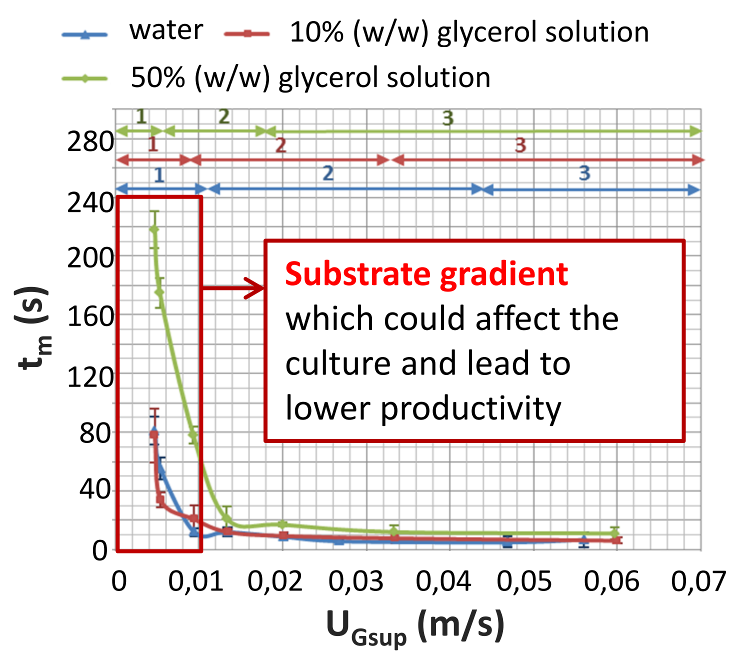
Terminal velocity of the bubbles reduced by a factor of 1.1 to 1.7

- Increased interactions between bubbles

	Transition	Heterogeneous
	U_{Gsup} (m.s^{-1})	U_{Gsup} (m.s^{-1})
Water	0.010	0.044
Water (Olmos, 2002)	0.030	0.065
50% w/w glycerol solution	0.006	0.017

Transition et heterogeneous regimes appear at low U_{Gsup} ➔ Limited Gas hold-up to stay in homogeneous regime

- Decrease in mixing capability at low gas superficial velocities



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Impact of confined hydrodynamics on G/L transfer

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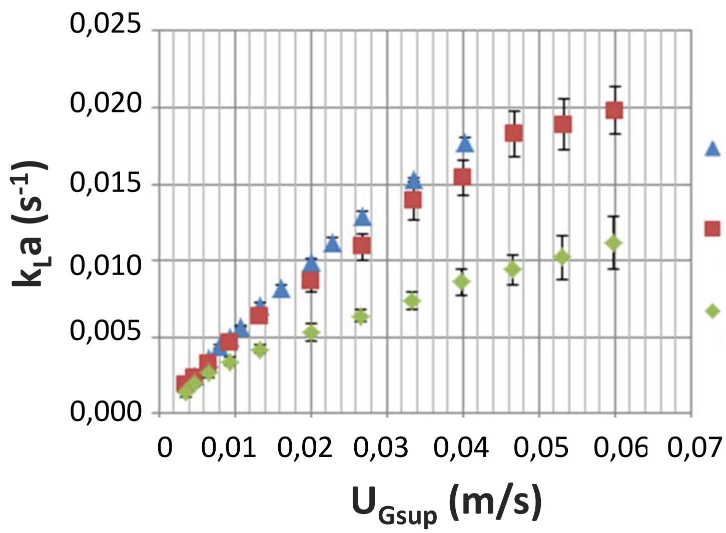
Importance of G/L mass transfer in PBR:

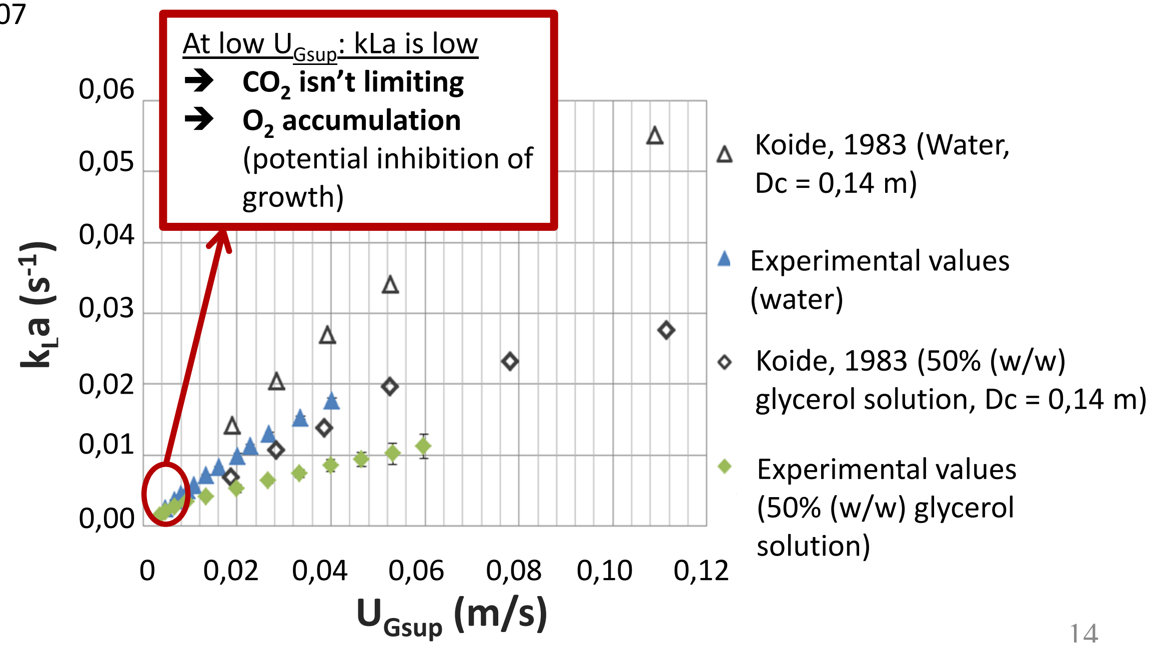
- Inorganic CO_2 is provided at the beginning (culture medium) and during culture (bubbling)
- Transfer must not limit growth and must prevent the accumulation of O_2



- k_La ↗ when U_{Gsup} ↗
- k_La ↘ when μ ↗

G/L mass transfer is worse at high cell density

- k_La ↘ in confined PBR (4 mm)



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Strategy to limit the development of biofilm

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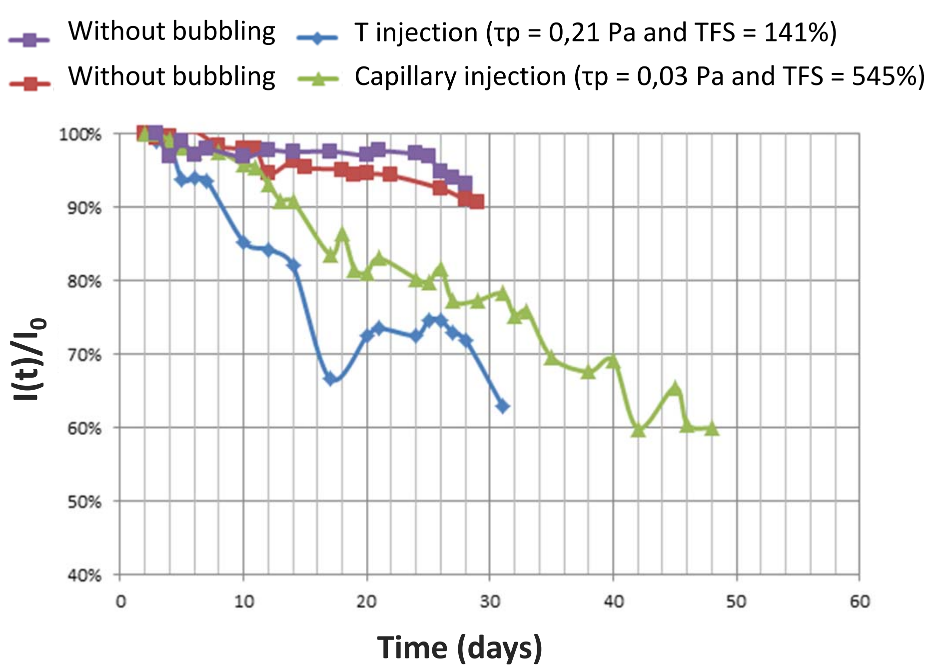
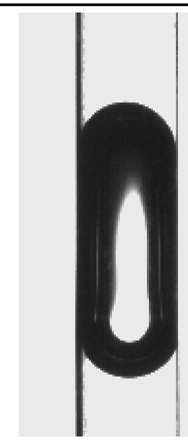
Use of bubbling to extend the time before biofilm development

- **Light intensity reduction through PBR walls during continuous culture**



Injections	T injection
τ (Pa)	**0,21**
TFS (%)	143%
F_{bubble} (Hz)	1,59
d_{Sauter} (mm)	7,1
V_{bubble} (m/s)	0,13
Shadowgraphy	

Avoid these types of bubbling → another strategy to be found

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Conclusion

- An intensified PBR was developed for microalgae production in artificial light: the PRIAM technology
- PRIAM technology combines intensification principles and modularity for a scalable production in a compact unit (up to 3.5-4kg/day)
- PRIAM present breakthrough performances compared to state-of-the-art technologies (x15-30 in volumetric productivity, x100 in daily production)
- Hydrodynamics reveals the main limiting factor: diphasic flows in confined geometry were especially investigated
- Research on the gas-liquid flow to reduce biofilm problem (patent in progress)
- Concept of PRIAM technology (compact intensified artificial light PBR) could be adapted to spatial constraints (no gravity)

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Thank you for your attention

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