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Microalgae culture in building-integrated photobioreactors: Biomass production modelling and energetic analysis

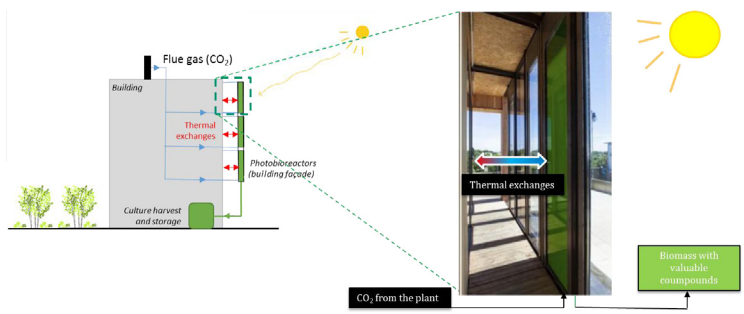
J. Pruvost [a,b,*], B. Le Gouic [a], O. Lepine [b], J. Legrand [a,b], F. Le Borgne [b]

[a] GEPEA, Université de Nantes, CNRS, UMR 6144, Bd de l'Université, CRTT – BP 406, 44602 Saint-Nazaire Cedex, France
[b] Algosource Technologies, Bd de l'Université, CRTT – BP 406, 44602 Saint-Nazaire Cedex, France

HIGHLIGHTS

- Vertical photobioreactor (PBR) integration in building facade was investigated.
- Results were compared to conventional systems (raceways, stand-alone PBR).
- The conditions then induced could benefit to the yearly PBR operation.
- Optimization of thermal exchanges between culture and building was critical.

GRAPHICAL ABSTRACT



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ABSTRACT

Vertical flat-panel photobioreactors for microalgae culture can be integrated into building facades. On top of providing the large solar illuminated surfaces needed for microalgae production, this original combination opens various optimization opportunities, such as the possibility to create mutual benefits for both systems with appropriate and efficient integration. For example, microalgal photosynthesis can be used to fix the CO_2 contained in flue gas emitted from the building (in a factory set-up) or to significantly reduce energy consumption for thermal regulation of both photobioreactors and building.

Here we report the results of a theoretical modelling-based investigation designed to define how the specific building integration conditions affect photobioreactor operation. Expected biomass production and light attenuation conditions encountered in the culture volume were determined for the green microalgae *Chlorella vulgaris* for a location based in Nantes (France). Results were compared to figures from the more conventional systems such as horizontal or ideally-inclined microalgal culture systems. We conclude with an energetic analysis that underlines the relevance of optimizing thermal exchanges between microalgal culture and building.

1. Introduction

Microalgae are emerging as a valuable new organic feedstock for an array of applications ranging from foods and feeds to cosmetics, pharmaceutical and biofuels [1,2]. Microalgae can be cultured in various systems, from open ponds to closed photobioreactors (PBR). Open ponds are cheap and easy to scale up, whereas closed-systems PBRs are notoriously expensive, which limits their use for mass-scale solar cultivation [3–9]. As a result, around 90% of current biomass production worldwide is obtained in open systems, despite the fact that PBR technologies offer greater potential in terms of productivity, control of culture conditions and applicability to cultivate various strains.

* Corresponding author at: GEPEA, Université de Nantes, CNRS, UMR 6144, Bd de l'Université, CRTT – BP 406, 44602 Saint-Nazaire Cedex, France. Tel.: +33 (0)2 40 17 26 69; fax: +33 (0)2 40 17 26 18.
E-mail address: jeremy.pruvost@univ-nantes.fr (J. Pruvost).

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The main objective in the industrial-scale deployment of this new technology today is to decrease PBR costs without compromising system performances. In this context, symbiosis with buildings appears a promising way to reduce the capital and operating costs of PBR technologies while at the same time bringing added-value benefits to the building, such as a partial reduction of its energy consumption or even effluent emissions. The large-scale illuminated areas are available, some costs like glazing can be shared, and the integration into a building facade allows fluid exchanges between building and PBRs to reduce thermal regulation and nutrient demands (especially if CO_2 sources are available in the building).

Optimization of exchanges (i.e. symbiosis) between the two systems is critical, as the ultimate utility of the concept here will result from mutual benefits between building needs and microalgae needs. A facade without PBR or a stand-alone vertical PBR will obviously be cheaper than an integrated solution, so only an optimized integration maximizing symbiosis between the two systems will result in a solution of interest.

Considering the PBR only, its installation on a building facade hinges on resolving a number of technical challenges. System geometry has to respond to architecture constraints, light capture has to be optimized to guarantee maximal performances, and the process has to be robust with ideally a continuous automated operation running for several months at a time. Relevant factors are system design and the mixing conditions applied or material used to avoid biomass fouling on glazed surfaces. The vertical-plane installation that on-facade integration entails adds a further major constraint. Although vertical installation is commonly encountered in PBR technologies like air-lift systems, it creates specific irradiation conditions that in turn create specific culturing conditions. Indeed, Pruvost et al. [6,10,11] showed a direct and strong correlation between light collected, photosynthetic growth, and resulting process response which is especially relevant for PBR technologies that are controllable enough to overcome any growth limitation other than light (the so-called "light-limited regime"). For a given microalgal strain, the process is then fully driven by light collected onto the cultivation system.

Appropriate consideration of the influence of sunlight on the cultivation system makes it possible to determine information of primary relevance like time-course of biomass concentration or biomass productivity. Modelling is especially useful here as it can relate the many complex phenomena involved in the conditions of solar culture, such as (1) time variations in sunlight in terms of intensity, beam–diffuse radiation partitioning, or collimated angle onto the PBR surface, and their effects on (2) radiative transfer in the culture volume and (3) the resulting photosynthetic conversion and biomass growth. This kind of approach has already been used, but only for standalone production units such as horizontally-fixed and solar-tracking systems, and mainly to investigate production limits or the effect of PBR location [10].

This work will extend our modelling approach to the particular case of flat-panel PBR integration in a building facade. More specifically, we investigate the case of integrating airlift PBR into the south-facing facade of a flue gas-emitting plant for simultaneous biomass production and CO_2 biofixation (SymBIO2 project). Maximal biomass productivity achievable (discussed here for the microalga *Chlorella vulgaris*) in such systems will be determined, and the resulting CO_2 biofixation capacity will be defined. The constraint of vertical installation will also be addressed by comparing results with standard cultivation systems (horizontal and inclined systems). The investigation will round up with an energetic analysis with special focus on energy requirements for thermal regulation to investigate the potential benefit of inducing thermal symbiosis with the supporting building. All these results will help characterize the utility, potential and limits of vertical building-integrated PBR.

2. Photobioreactor integration into the building facade

2.1. Context of the study

Symbio2 is an industrial R&D project with a brief to develop advanced hybrid facade systems that optimize the concept of symbiosis between building and microalgal cultivation by integrating flat-panel microalgae PBRs enabling optimized exchanges with the support building so as to decrease thermal needs and enable CO_2 biofixation for a flue-gas-emitting building—in this case a waste processing plant.

Given the lack of relevant literature, a set of preliminary investigations was planned to address the most relevant aspects of this complex process, i.e. (1) culture conditions induced by installing a PBR on a vertical facade, (2) conservative estimates of achievable biomass productivity, (3) interest of inducing thermal exchanges with the support building, (4) hydrodynamic optimization of the flat-panel PBR to prevent fouling on optical glass surfaces, and (5) validation of the concept in real outdoor operating conditions. This paper reports the results of these preliminary investigations, except for the hydrodynamics and real-outdoor investigations which are currently in progress.

2.2. Thermal regulation of solar PBRs: how to benefit from building integration

Like with any biological process, temperature directly influences photosynthesis and microorganism growth. Under high solar illumination, closed PBRs tend to overheat while open systems can suffer water evaporation issues, both of which can be attributed to culture confinement and to the strongly exoenergetic photosynthetic growth [12–15]. In fact, the thermodynamic efficiency over the PAR region of systems working with the low light regimes typical of artificial illumination (100–300 $\mu mole_{h\nu}\, m^{-2}\, s^{-1}$) is generally below 5% [16], decreasing to 2% under large solar irradiance (>500 $\mu mole_{h\nu}\, g^{-2}\, s^{-1}$). In addition, under outdoor conditions, around 50% of the energy in the solar radiation is contained in the near- and mid-infrared above 750 nm and directly participates in heating up the culture [15,17–19]. As a result, around 95% of the captured total light spectrum energy is converted into heat.

Thermal regulation of PBRs has been widely investigated as a major issue of solar microalgal cultivation [15,18,20,21]. The appropriate temperature window is strongly dependent on species cultivated, but typically ranges between 10 and 30 °C. Unfortunately, without proper thermoregulation, temperatures lethal to living microorganisms can easily be reached inside the PBR when exposed to solar light. On the other hand, in temperate climates, excessively low temperatures during winter can result in loss of biomass growth and productivity, in which case culture heat-up becomes can be beneficial [17]. Year-round operation can create then a need for both cooling and heating.

Various solutions have been developed for heating or cooling PBRs depending on PBR technology, size, and location. Cooling and/or heating by spraying water on the PBR's outer surfaces or by direct immersion in a pool are often used [20]. In temperate regions, microalgae culture systems can also be placed in greenhouses. Although efficient, those methods can increase the construction and operating costs and negatively impact the environmental footprint through excessive energy and water consumption.

Although technical solutions currently exist, PBR temperature control remains a challenge under solar conditions, especially if the aim is to find cost-effective, low-energy-demand, year-round-operable solutions. The engineering of the cultivation system is equally relevant. For example, Goetz et al. [19] experimentally