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Theoretical investigation of microalgae culture in the light changing conditions of solar photobioreactor production and comparison with cyanobacteria

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ABSTRACT

Modeling was performed to investigate solar production of the microalga *Chlamydomonas reinhardtii* in photobioreactors (PBRs). Maximal biomass productivity achievable on Earth was calculated (ideal reactor concept). Effect of PBR location and of given operating conditions was simulated. An ideal productivity (upper limit) in the range of 60 t_x ha^{-1} $year^{-1}$ was obtained for a fixed horizontal PBR. For a facility sited in France (Nantes), a maximal biomass productivity of around 37 t_x ha^{-1} $year^{-1}$ was predicted.

The comparison against the cyanobacterium *Arthrospira platensis* highlighted the marked influence of non-ideal light attenuation conditions in the culture volume when growing microalgae. Not only light transmission but also dark volumes were found to negatively impact biomass productivity. Consequently, as biomass growth rate is unable to compensate for rapid changes in sunlight intensity, it proved impossible to maintain optimal light conversion throughout time in outdoor solar conditions. The outcome was a significant decrease in expected productivities, in contrast to cyanobacteria where appropriate optimization resulted in actual productivities approaching the maximal achievable productivities. For microalgae, productivity optimization promoted low light attenuation to safeguard against the marked negative influence of dark volume on microalgae growth. If combined with high PFD, this could impair PBR stability in solar use.

1. Introduction

Photosynthetic microorganisms such as microalgae and cyanobacteria have emerged as a new high-potential farmable bioresource [1,2]. Their main advantages are solar production with higher surface productivities than plants, and a simultaneous consumption of inorganic carbon which enables carbon-neutral operation. When production is run in closed systems, it offers several additional advantages including an intensified and controlled production with very low environmental impact (no fertilizer is released and water can be re-used). These features, combined with the high biodiversity of microalgae, open up an array of potential feedstock applications as new raw materials for green chemistry or biofuels [3–7].

One of the key aspects in the deployment of microalgal-based industrial applications is the setting of efficient and controlled solar cultivation systems for mass production [2,8–12]. This implies technological development of suitable processes, but also the system-wide optimization of biomass productivity when working in outdoor solar conditions.

The photosynthetic conversion process means that biomass productivity is closely dependent on the light collected. However, unlike other conventional solar technologies such as photovoltaic panels or surface-supported photocatalysis, light is converted inside a given culture volume, which makes it difficult to predict the resulting productivity as it depends not only on the irradiation conditions but also on the transfer of the collected light flux inside the bulk culture in which light conversion by photosynthetic microorganisms occurs. The prediction of resulting productivity is thus far from trivial. Here, modeling emerges as an especially interesting way forward, as shown by several recent works on solar PBR cultivation [13–18], all of which conclude on the complex relation between irradiation conditions, PBR design, internal light attenuation conditions, and resulting growth. At this juncture, simulation is especially valuable for predicting and optimizing productivities as a function of PBR design, location, and cultivated species.

We recently presented a model able to simulate solar PBR [17–19]. This model was developed for the specific case of light-limited conditions in which light alone limits growth, assuming that all other biological needs (nutrients, dissolved carbon) and operating conditions (pH, temperature) are controlled at optimal values. It was based on a detailed determination of the irradiance field inside the PBR, taking into account

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specific features of solar use such as (i) the direct/diffuse radiation proportions in sunlight and (ii) time-variation in incident light flux and the corresponding incident angle on the PBR surface. This determination was then coupled with the local kinetics of photosynthetic growth of the cultivated species, paving the way to simulating PBR productivity and its transient response to day-night cycles.

It is well-known that photosynthetic microorganisms absorb light. As a result, photosynthetic growth, and thus process productivity, is deeply affected by light attenuation conditions in the culture volume. In solar conditions, stochastic variation in radiation conditions means that day-long light attenuation conditions are not constant. The process is therefore always running in transient mode, which means efforts to optimize biomass productivity to find a compromise on light attenuation conditions applied in the photobioreactor, for example by controlling biomass concentration value with residence time in the cultivation system. As shown in our previous works [17,18], modeling proved a highly interesting way forward due to its ability to relate variations in radiation conditions, resulting radiative transfers in the culture bulk, and the corresponding photosynthetic conversion and biomass growth kinetics.

In this previous work, modeling was applied to solar cultivation of the cyanobacteria *Arthrospira platensis*. Cyanobacteria, as prokaryotic cells, have a common electron carrier chain for both photosynthesis and respiration, in contrast to microalgae (eukaryotic cells) which have two different organelles for the two activities (respiration in mitochondria, photosynthesis in chloroplasts). As a result, cyanobacteria display negligible respiration for short residence times in darkness, in contrast to microalgae in which respiration activity is always active [20]. These features greatly influence the resulting productivity in cultivation systems, especially the dark volume created in the culture bulk due to light attenuation. This was clearly shown in Takache et al. [21] in the case of continuous artificial light. With light attenuation conditions presenting dark zones in the culture volume, the biomass productivity of the microalga *Chlamydomonas reinhardtii* decreased significantly. As any light transmission also resulted in a loss of productivity (as not all available light energy gets absorbed and thus converted), maximal biomass productivity was only found for an optimal biomass concentration value, leading to the so-called "luminostat" regime. Conversely, maximal productivity was achieved for cyanobacteria as soon as full light absorption in the culture volume was obtained with a negligible influence of dark volume in the culture bulk (light transmission resulting in a loss of productivity in any case).

The aim of this work is to investigate consequences of the typical microalgae behavior under changing light attenuation conditions of solar cultivation. Our earlier modeling approach will be extended here to the particular case of solar production of the microalga *C. reinhardtii*, which we chose based on its status as a model species for eukaryotic photosynthetic microorganisms and its recently published and validated kinetic growth model [21]. As in the case of *A. platensis*, the model will be used to determine maximal achievable productivity on Earth (mobilizing the concept of "ideal reactor") and to then investigate the influence of geographic location, engineering (i.e., PBR inclination angle) and operating parameters (i.e., residence time) on resulting productivity over a whole-year period. We conclude with a detailed discussion on the light attenuation conditions then encountered in solar operation, emphasizing that the optimization of microalgae cultivation in solar conditions is a more complex challenge than for cyanobacteria.

2. Methodology

2.1. Theoretical considerations

2.1.1. Solar photobioreactor modeling

Recent research has brought a model for simulating PBR operated in solar conditions [17–19]. The main features are given in Appendix A, and the interested reader can refer to the relevant literature. The model relates radiation conditions to biomass production, radiative transfer in the culture volume, and then the resulting photosynthetic growth. By linking the respective kinetics of photosynthetic growth and sunlight variations, the model makes it possible to predict biomass growth represented by time-course of biomass concentration as a function of light collected by the system (Fig. 1). Production can then be determined for a whole-year period, thus yielding data such as biomass productivity.

2.1.2. Modeling photosynthetic growth for cyanobacteria and microalgae

Our earlier modeling approach which was restricted to the cyanobacteria case was extended in this work to the solar production of microalgae. Cyanobacteria, as prokaryotic cells, display negligible respiration for short residence times in darkness, in contrast to microalgae in which respiration activity is always active [20]. As a consequence, a dark zone in the culture volume promotes respiration resulting in a loss of biomass productivity. Therefore, achieving the maximum biomass productivity requires in this case the exact condition of complete absorption of the incident light [22], but without a dark zone in the culture volume. This condition is often referred to as luminostat mode.

Maximum biomass productivity can be easily achieved in continuous PBR exposed to artificial constant illumination by setting the biomass concentration corresponding to optimal light attenuation conditions [22]. Under sunlight, the biomass growth rate is not sufficient to compensate for the rapid changes in sunlight intensity. Consequently, light attenuation conditions are never optimal. The purpose of this study was to investigate consequences of such typical behavior of microalgae on solar PBR production.

The consideration of microalgae case implied only to modify the growth kinetic relation in the model (see Appendix A for the remaining parts of the model). To make the kinetic coupling presentation comprehensible two different kinds of metabolism are involved (i.e., cyanobacteria and microalgae), we adopted a unified point of view using a formulation for specific rates of O_2 evolution in both cases. The growth kinetic relation giving local photosynthetic specific oxygen evolution rate for the cyanobacterium *A. platensis* is [23,24]:

$$J_{O_2} = \rho \overline{\phi}'_{O_2} \mathrm{A}\, \mathcal{H}(G-G_c) = \rho_M \frac{K}{K+G} \overline{\phi}'_{O_2} E_a G \mathcal{H}(G-G_c) \quad (1)$$

where $\mathcal{H}(G-G_c)$ is the Heaviside function ($\mathcal{H}(G-G_c)=0$ if $G<G_c$ and $\mathcal{H}(G-G_c)=1$ if $G>G_c$), ρ_M is maximum energy yield for photon conversion, $\overline{\phi}'$ is the mole O_2 quantum yield for the *Z* scheme of photosynthesis, and *K* is the half-saturation constant for photosynthesis.

This equation is valid for prokaryotic cells like *A. platensis* that display negligible short-time respiration in darkness. For microalgae (eukaryotic cells), growth in light would be the result of the evolution in O_2 caused by photosynthesis in chloroplasts and its partial degradation by respiration in mitochondria. It is thus necessary to introduce an appropriate kinetic formulation taking into account respiration at light. This was recently proposed for the microalga *C. reinhardtii* in Takache et al. [21], leading to a similar form to Eq. (1):

$$J_{O_2} = \left[\rho \overline{\phi}'_{O_2} \mathcal{A} - \frac{J_{NADH_2}}{\upsilon_{NADH_2-O_2}} \times \frac{K_r}{K_r+G}\right] = \left[\rho_M \frac{K}{K+G} \overline{\phi}'_{O_2} \mathcal{A} - \frac{J_{NADH_2}}{\upsilon_{NADH_2-O_2}} \times \frac{K_r}{K_r+G}\right]. \quad (2)$$

This formulation introduces a specific term relating the negative contribution of respiration activity to overall growth rate. In this term, J_{NADH_2} is the specific rate of cofactor regeneration on the respiratory chain, linked to oxygen consumption by the stoichiometric coefficient $\upsilon_{NADH_2-O_2}$ (the stoichiometric coefficient of cofactor regeneration on the respiratory chain), and K_r is a saturation constant describing the