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Microalgae Flat Plate-Photobioreactor (FP-PBR) System Development: Computational Tools to Improve Experimental Results

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Abstract

The new multifunctional "Algae Lab" was established by our research team in West Parana State University of Toledo. Several microalgae strains were isolated and identified by applying modern molecular techniques. The system analysis theory was applied when developing and designing novel flat plate photobioreactors (FP-PBRs). One of the objectives of this study was to use computing fluid dynamics (CFD) simulations in order to support the scale up procedure of (FP-PBRs). The improved hydrodynamics of the construction reflected in optimal flashing-light effects and yielding in high cell density cultures.
Keywords: algae Lab, flat plate photobioreactors, microalgae

Резюме

Нова многофункционална «Лаборатория за водорасли» бе създадена от нашия изследователски екип в Университета на Западна Парана в Толедо. Няколко щама микроводорасли бяха изолирани и идентифицирани чрез прилагане на съвременни молекулярни техники. Теорията на системния анализ бе приложена при разработването и проектирането на нови плоски- фотобиореактори (П-ФБР). Една от целите на това изследване е да се използват симулации при изчисляване динамика на флуидите (ИДФ), за да се оптимизира процедурата по мащабиране на (П-ФБР). Подобрената хидродинамика на конструкцията се отразява в оптималните «светлинни мигащи ефекти»и добива на култури с висока клетъчна плътност.

Introduction

Microalgae have been the focus of many scientists around the world for many years, mainly due to their important role in the atmosphere CO_2 remediation process. In this sense, microalgae can act both by preventing the CO_2 from going into the atmosphere, through the production of biofuels, and by reducing the CO_2 levels from the air, through the photosynthesis process.

Biofuels play an important role in the current economy, since the dependence of human beings on petroleum has increased significantly due to the large industrialization and transportation, which has led to an increase in crude oil prices, besides global warming (Malcata, 2011). In this context, microalgae present various advantages when compared to ground plants, such as the production of 30 to 100 times higher than plants by hectare (Demibras, 2010), which reduces significantly the space needed. It has been reported that some microalgae can produce as much as 80% oil of their dry cell weight. Their year-round production and very high growth rates make them a superior source of biodiesel production (Brennan and Owende, 2010; Borowitzka and Moheimani, 2013; Milano *et al.*, 2016; Olofintuyi *et al*., 2016; Thomas *et al*., 2016). Besides that, microalgae can grow anywhere in open ponds, closed photobioreactors (PBRs) and waste water of wide pH range and chemical composition. In this context, there are several different biofuels that can be produced from microalgae biomass, such as biodiesel (Cheng *et al.*, 2015; Kokkinos *et al*., 2015; Maranduba *et al.*, 2016; Sharma *et al*., 2016), bioethanol (Fasahati *et al.,* 2015; Hernández *et al*., 2015; Simas-Rodrigues *et al*., 2015; Saïdane-Bchir *et al*., 2016), biohydrogen (Sambusiti *et al*., 2015; Torzillo *et al*., 2015; Eroglu and Melis, 2016) and biogas (Klassen *et al*., 2015; Neves *et al*., 2016; Santos-Ballardo *et al.,* 2016).

Besides their role in reducing global warming, microalgae are also capable of synthesizing high value products (HVP), such as pigments (Macintyre *et al*., 2002; Dufossé *et al*., 2005; Pasquet *et al*., 2011), polyunsaturated fatty acids (Thepenier *et al*., 1994; Furuhashi *et al*., 2016), biologically active compounds – antibacterial, antifungal, antiviral, antitumor (Borowitzka, 1995; Mendes *et al*, 2003; Ördög *et al*., 2004; Mimouni *et al*., 2012; Skjånes *et al*., 2013) among others.

With all that in mind, it is of the uttermost importance to optimize microalgae growth systems, mainly with closed PBRs, such as column or flat-plates, due to the possibility of better controlled operational parameters. Among the closed PBRs, the flat-plate (FP-PBR) are well known because of their capacity to produce high cell concentration, which is mainly due to the small trajectory that the light needs to penetrate inside the PBR (distance between the plates) (Richmond and Cheng-Wu, 2001).

When evaluating microalgae biomass growth in novel PBRs, the key parameters that must be taken into account are nutrient concentration in the medium, light availability and distribution, CO_2 concentration in the inlet gas and its speciation in water, pH and temperature (Kroumov *et al*., 2016; Kroumov *et al*., 2017). In order to reduce experimental efforts, computer simulations are important tools for the optimization of the process.

Materials and Methods

Since microalgae growth in FP-PBRs is a very complex process, with many variables and operational parameters that must be taken into account, the use of the System Analysis Theory is very interesting, since it divides the process into subsystems and hierarchic levels, which are studied separately, as shown in our previous work (Kroumov *et al.*, 2016). Figure 1 shows a simplified scheme of the system and its divisions.

For both the first and second hierarchic levels of knowledge, computer simulations are very interesting to evaluate various different scenarios at a low cost and high efficiency. Thus, this paper aims to present how mathematical modeling and computer simulations can help improve microalgae growth and biomass production when developing novel FP-PBRs.

First hierarchic level of knowledge – Kinetic modeling

As seen in Fig. 1, the first hierarchic level of knowledge consists of the physiological study of the microalgae cells, taking into account their requirements and tolerances towards the operational parameters.

When studying microalgae growth in a determined PBR, mathematical modeling has proved to be a powerful tool to reduce work efforts and

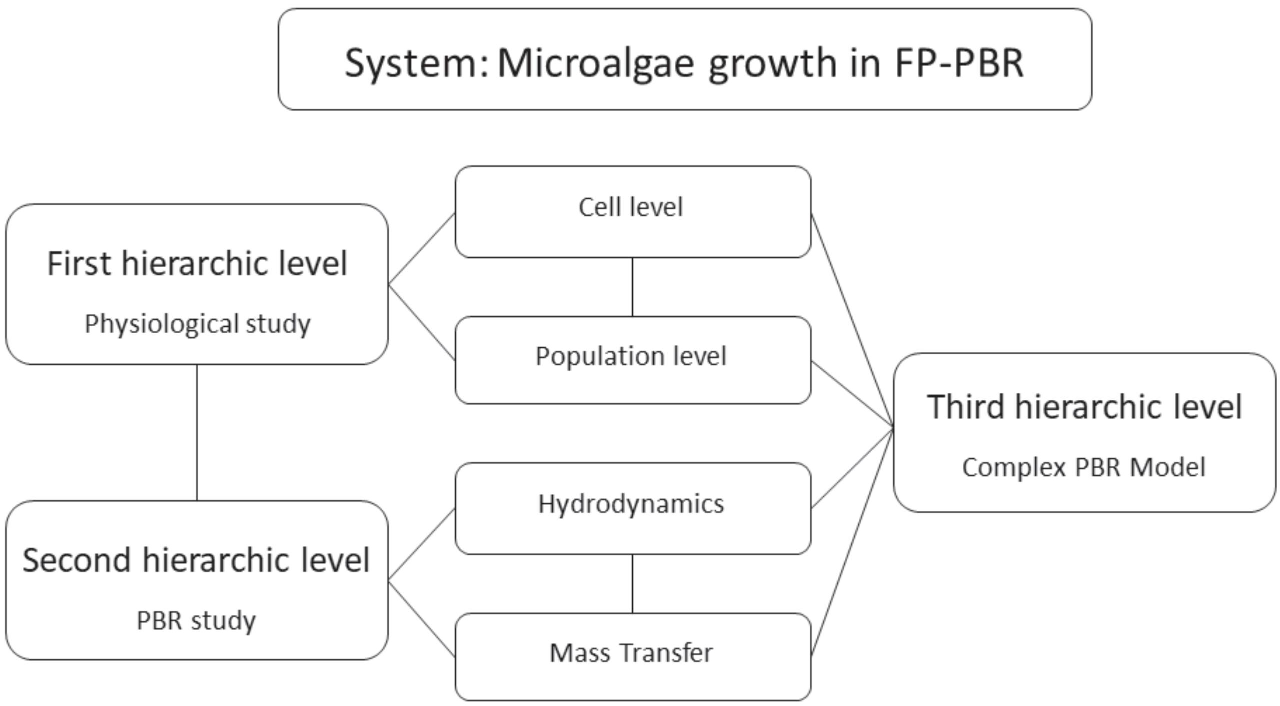

Fig. 1. Simplified scheme of the FP-PBR system divided into three hierarchic levels of knowledge

process development costs. In order to build a complex model that is able to describe cells growth in a FP-PBR, some different concepts must be taken into account, such as the CO_2 and SO_2 dissociation reactions in water (when used flue gas), mass transfer between gas and liquid, the definitions of specific transformation rate and conversion, as well as Henry's law.

Second hierarchic level of knowledge – Hydrodynamics simulations

It has been extensively reported that the movement of the fluid inside a PBR greatly influences its productivity, since it is responsible for various factors, such as mixing, CO_2 solubility, gas holdup and, most important, light availability. This is because the movement of the fluid is responsible for getting microalgae cells close to the reactors walls, where they can absorb light energy, and then move them back to the inner portion of the PBR, the dark part, where they can finish the photosynthetic process as well as recuperate their photosynthetic machinery. This is called the flashing-light effect, which promotes very fast light-dark (L/D) cycles.

In order to study the fluid dynamics of different FP-PBR configurations, there are several software packages that can be used to simulate the flow by applying mathematical models that describe multiphase fluid flows. The two most common approaches to model multiphase flux considering air bubbles are the Euler-Euler, which considers both phases (continuous – liquid and disperse – gas) as interpenetrating continua, and the Euler-Lagrange, which uses the volume-averaged Navier-Stokes equations to describe the motion of the liquid while tracking down each bubble (Mousavi *et al*., 2008).

Considering that in microalgae production in a PBR the disperse phase fraction is high, tracking down each bubble can become hard work, demanding a lot of computer processing. Thus, there have been reports (García *et al*., 2012) that the Euler-Euler model is the best choice in this case, since it is simple and demands less computational work, giving satisfactory results (Krishna *et al*., 2000; Bitog *et al*., 2011; Studley and Battaglia, 2011) even though it loses accuracy since it does not take coalescence or bubble breakage into account. In the Euler-Euler model, the movement of the fluid is modeled through its equations of mass and momentum conservation.

In FP-PBRs, one way to improve the fluid movement towards the flashing-light effect is through the addition of baffles that force the liquid to go a certain way. By using computational simulations, one can evaluate the flux of various different PBR configurations without all the laboratorial work.

Third hierarchic level of knowledge

The third hierarchic level (complete PBR model) can be considered as a final step in a modeling process. At this level all valuable knowledge from previous levels can be combined and preserved into the complete PBR mathematical model. Verification of the model at this level is not an easy task and most probably requires a loop procedure, where real experiments are performed with PBR (preferably in a pilot plant scale) to correct and prove the hypothesis assumed in previous levels. Scale-up and scale-down procedures here worked powerfully. In any case of PBR design, these studies can vary, but this is only one goal to obtain a robust complete PBR model, which will be applied for its scale up. Our studies on this subject received their complete form and were published elsewhere (Kroumov *et al*., 2016). In this paper we showed in details our approach on how to model and study column PBR constructions when using flue gas as a source of CO_2 for autotrophic microalgae growth. Computer simulations with the complex PBR mathematical model taking into account knowledge from hydrodynamics and microalgae kinetics were demonstrated by advanced research groups (Nahua and Alopaeus, 2013). The application of such an approach for different systems was successful throughout our 30 years of research with bio-, photobioreactors and other systems. We applied this knowledge to create a new multifunctional "Algae Lab" in West Parana State University of Toledo under the CNPq grant "Science without borders" #400771/2014-4.

Results and Discussion

As mentioned above, a new multifunctional "Algae Lab" was created by our research team. The topics of the lab included studies in the following hottest areas of:

- <u>Algal physiology, taxonomy, and morphology</u>;

- <u>Algae isolation</u>: By using standard methods for algae isolation and preservation, we were able to locate regions rich in algae species and take samples from there. Several promising algae species (Fig. 2) were isolated and are currently being used in our Lab.

- <u>Algae identification</u>: By applying modern molecular techniques for molecular identification of microalgae we were able to identify the species

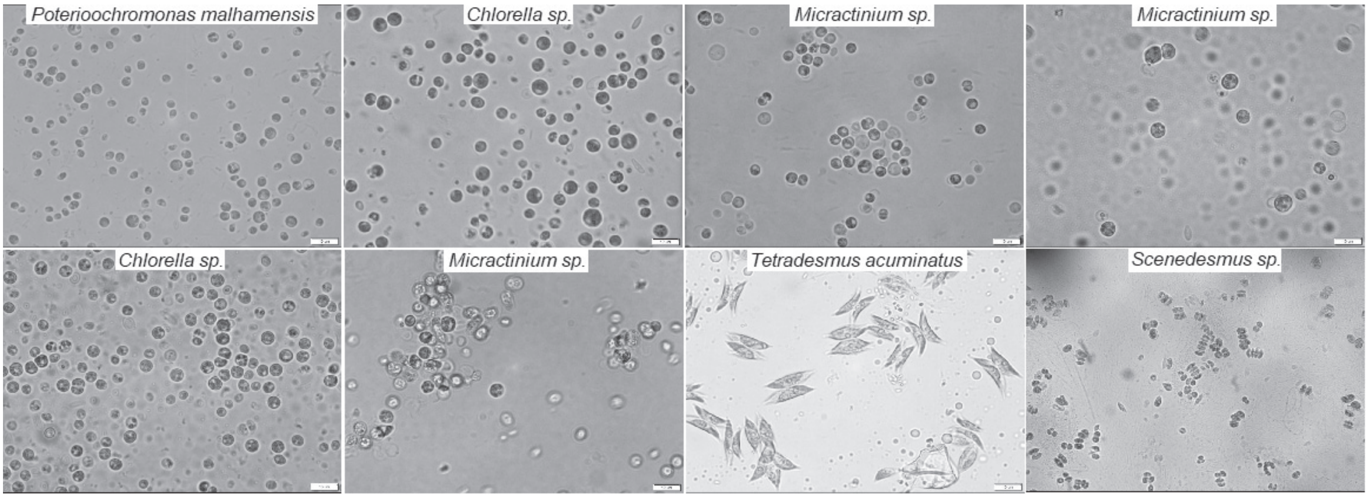

Fig. 2. Strains isolated in the new multifunctional "Algae Lab"-UNIOESTE-Toledo

Poterioochromonas malhamensis, Chlorella sp., Micractinium sp., Tetradesmus acuminatus and *Scenedesmus sp.*, as shown in Fig. 2.

- Algae cultivation: Having in mind the specifics of microalgae, their ability to produce bioactive compounds under autotrophic, mixotrophic and heterotrophic growth, we were checking the metabolic ability of every selected algae species under such conditions; Application of cultivation techniques to ensure optimal light-dark cycles conditions and "flashing light effects" in the chosen PBR vessel.

- Medium optimization: Our previous studies included the robust methodology to calculate the recipe of nutrients medium components and their optimization by applying linear programming and chemical elements presence in the microalgae cells. The complete study on this subject can be found elsewhere (Kroumov *et al*., 2015).

- Algae selection on the basis of their potential to produce different biologically active compounds: Several isolated (Fig. 2) microalgae species with potential to produce bioactive compounds were cultivated under specific light specter spectrum conditions and promising results were achieved (Gonçalves *et al*., 2017).

- Global biorefinery concept: This concept was discussed in details elsewhere (Kroumov *et al.*, 2017). All the studies in the Algae Lab have been conducted under this complex concept.

- PBR design – different types and scale of PBRs (Fig. 3) were set up by applying system analysis theory on how to study and model the PBRs. Special attention was given to kinetics and hydrodynamics studies and their relationship.

- Algae as promising source of low value products – bio-fuels, proteins, etc. The new isolated and identified *P. malhamensis* strain was cultivated in two 10L FP-PBRs (see Fig. 3) under many different cultivation conditions and this strain showed potential to be used for CO_2 sequestration from waste gases rich in CO_2.

- Kinetics studies with promising selected strains in PBRs of different scale; kinetics studies were a milestone for the overall process and FP-PBR development. Our first detailed study on microalgae kinetics was executed by using new isolated, identified and selected *P.malhamensis* strain (Fig. 2).

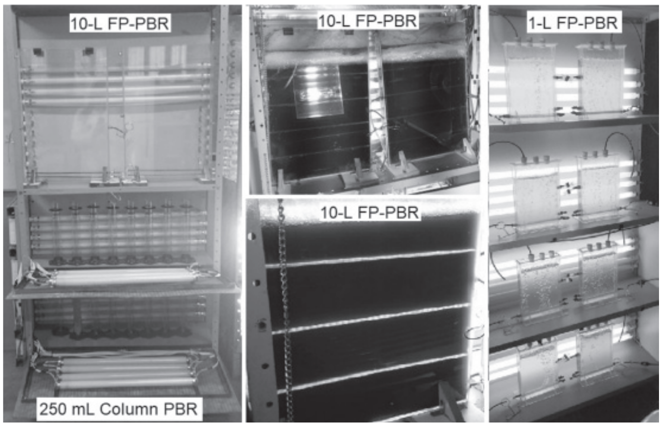

Fig. 3. Different PBR types and volumes design for microalgae growth

- Hydrodynamics studies: hydrodynamics was studied by mathematical models, and the movement of the culture inside the FP-PBR was simulated by using computational fluid dynamics CFD software. Along with that, the flashing-light effect was evaluated, as well as the role it plays on microalgae growth. This study showed an improvement of about 250% on cell growth when using an internal bubbles disperser, which changed the fluid movement towards the flashing-light effect.

- Development of different scenarios of application of the strains products covered with engineering specification.

- Pilot plant studies with new PBR constructions in order to cover a wide possibility of knowledge transfer to industrial scale.

Conclusion

The new multifunctional Algae Lab" was established by our research team in West Parana State University of Toledo. Our research team has set ambitions goals for the studies which will be performed in it. The preliminary three-year study has shown that the chosen strategy works well and has highlighted new insights and new unexpected challenging directions in algology area.

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