Modelling the impact of temperature on microalgae productivity during outdoor cultivation

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Abstract

Accurate predictions of algal productivity during outdoor cultivation are critically needed to assess the economic feasibility and the environmental impacts of full-scale algal cultivation. The literature shows that current estimations of full-scale productivities are mainly based on experimental data obtained during lab-scale experiments conducted under conditions poorly representative of outdoor conditions. In particular, the effect of temperature variations on algal productivity is often neglected. The main objective of this thesis was to develop a model able to predict algal productivity under the dynamic conditions of temperature and light representative of full-scale cultivation. In a first step, models were developed to predict broth temperature as a function of climatic, operational, and design parameters. The model developed for open ponds could predict temperature at an accuracy of ±2.6^{o}C when assessed against experimental data collected in New Zealand over one year. The temperature model developed for closed photobioreactors was accurate at ±4.3^{o}C when compared to experimental data collected in Singapore and New Zealand over a total of 6 months of cultivation. This second temperature model was then applied at different climatic locations to demonstrate that actively controlling temperature would seriously threaten the economics and sustainability of full-scale cultivation in photobioreactors.

To quantify the impact of temperature variations on biomass productivity, a productivity model was developed using *Chlorella vulgaris* as a representative commercial species. To determine the best methodology, a review of more than 40 models described in the literature revealed that an approach accounting for light gradients combined with an empirical function of temperature for photosynthesis and first-order kinetics for respiration would offer the most pragmatic compromise between accuracy and complexity. The model was parameterized using short-term indoor experiments and subsequently validated using independent bench-scale indoor (> 160 days) and pilot-scale outdoor (> 140 days) experiments, showing prediction accuracies of ± 13%. The outdoor data set was obtained from 13 different experiments performed in 4 different reactors operated under various regimes and climatic conditions. The productivity model was found to be accurate enough to significantly refine previous assessments of the economics and the environmental impacts of full-scale algal cultivation.

The productivity model was then used in different case studies in order to investigate the impact of location/climate, design (pond depth or reactor diameter), and operation (hydraulic retention time or HRT) on productivity and water demand. Although the qualitative impact of the HRT on process was already known, this application enabled the first quantification of the HRT value on the productivity. Low HRT values around 3 days were found to maximize productivity at most locations investigated but these operating conditions were associated with a large water demand, illustrating a poorly acknowledged trade-off between sustainability and revenues. The model was also used to demonstrate that actively controlling the pond depth can increase the productivity by up to 23% while minimizing the water demand by up to 46%. This thesis therefore revealed that the choice of a location for algal full-scale production must be based on the comparison of optimized systems, contrarily to current assessments assuming the same design and operation at different locations.

Preface

In the 90s, the terrestrial plant *Jatropha curcus* was considered as a prime candidate for biofuel production. For example, Foidl et al. (1996) concluded that "for developing countries […] *Jatropha curcus* seems to be a very promising energy plant. The plant can be grown on very poor soil and gives a high yield of seeds". Driven by these initial observations, the cultivation of Jatropha was encouraged by India and China on a large scale. In 2008, Jatropha was cultivated on 900,000 hectares of land (Kant and Wu, 2011). However, the actual productivities were far below expectations, for reasons that Kant and Wu (2011) qualified as "nothing out of the ordinary and [which] should have been anticipated". Indeed, the initial studies were carried under conditions that did not represent full-scale cultivation conditions. In particular, even if Jatropha can survive in a dry environment, the seed production only happens when the plant is cultivated in wet and warm conditions that are often not met on marginal lands (Weyerhaeuser et al., 2007).

With the same objective to replace fossil fuels with sustainable fuels, microalgae received the same enthusiasm than Jatropha two decades earlier. For example, Chisti (2008) claimed that "biodiesel from microalgae seems to be the only renewable biofuel that has the potential to completely displace petroleum-derived transport fuel without adversely affecting supply of food and other crop products." Similar claims were made by Leite et al. (2013): "The production of biofuels using microalgae is promising since of all photosynthetic organisms they have the highest growth rates, and they can be cultivated using non-arable land with wastewater as a source of nutrients." However, the assessments of the biofuel production from microalgae are based on observations in indoor laboratories where algae were cultivated under ideal conditions that do not represent full-scale conditions. Moving to full-scale algal cultivation for biofuel production may therefore lead to reproduce the "extraordinary collapse of Jatropha" denounced by Kant and Wu (2011). This is the main motivation for the work undertaken in this thesis.

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Structure of the thesis

This thesis is based on six scientific articles attached as appendix at the end of this thesis (four of which have been published). The content of these articles supports the conclusions provided in this thesis. To avoid redundancy (especially the description of materials and methods) or discussion of information not strictly relevant to this thesis (e.g. water footprint in Article 6), the chapters were organized and written based on the articles rather than from the articles. Key results and findings are referred to corresponding articles wherever relevant.

List of Articles and contribution

Article 1: Béchet Q, Shilton A, Guieysse B. 2013. Modelling the effects of light and temperature on algae growth: State of the art and critical assessment for productivity prediction during outdoor cultivation. Biotechnology Advances 31(8): 1648-1663. (2012 Impact factor: 9.599; Number of citations[1]: 5)

Contribution to the article: Q Béchet was the main contributor to the review. In particular, the classification of productivity models was originally proposed by Q Béchet.

Article 2: Béchet Q, Shilton A, Park JBK, Craggs RJ, Guieysse B. 2011. Universal temperature model for shallow algal ponds provides improved accuracy. Environmental Science & Technology 45(8): 3702-3709. (2012 Impact factor: 5.257; Number of citations: 15)

Contribution to the article: Q Béchet was the main contributor to the article. He constructed and numerically implemented the temperature model. The experimental data used for model validation were provided by the New Zealand National Institute for Water and Atmospheric Research (NIWA).

Article 3: Béchet Q, Shilton A, Fringer OB, Muñoz R, Guieysse B. 2010. Mechanistic modeling of broth temperature in outdoor photobioreactors. Environmental Science & Technology 44 (6): 2197-2203. (2012 Impact factor: 5.257; Number of citations: 25)

Contribution to the article: Q Béchet was the main contributor to the article. He constructed and numerically implemented the temperature model. He also collected the experimental data used for model validation.

Article 4: Béchet Q, Chambonnière P, Shilton A, Guizard G, Guieysse B. Algal productivity modeling: a step toward accurate assessments of full-scale algal cultivation (submitted).

[1] According to Google Scholar Citations on the 02/07/2014

Contribution to the article: Q Béchet supervised the student P Chambonnière who performed most of the experimental work for model parameterization and the associated data analysis. Q Béchet did the experimental work for model validation and associated simulations. He also wrote most of the article.

Article 5: Béchet Q, Shilton A, Guieysse B. Full-scale validation of a model of algal productivity (submitted).

Contribution to the article: Q Béchet was the main contributor of the article. He carried the experimental work and analyzed the results (including the numerical implementation of the model). He also wrote most of this article.

Article 6: Guieysse B, Béchet Q, Shilton A. 2013. Variability and uncertainty in water demand and water footprint assessments of fresh algae cultivation based on case studies from five climatic regions. Bioresource Technology 128: 317–323. (2012 Impact factor: 4.750; Number of citations: 10)

Contribution to the article: Q Béchet performed the calculations of water demand and water footprint of algal cultivation in open ponds by using the code he developed for Article 2.

Note: Even if Article 6 discusses the water footprint of algal cultivation, this metric will not be discussed in this thesis as its relevance is uncertain (see the discussion section of Article 6 for further details). In this thesis, only the water demand will be considered to discuss the environmental impacts of full-scale cultivation.