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Research review paper

Modeling the effects of light and temperature on algae growth: State of the art and critical assessment for productivity prediction during outdoor cultivation

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The ability to model algal productivity under transient conditions of light intensity and temperature is critical for assessing the profitability and sustainability of full-scale algae cultivation outdoors. However, a review of over 40 modeling approaches reveals that most of the models hitherto described in the literature have not been validated under conditions relevant to outdoor cultivation. With respect to light intensity, we therefore categorized and assessed these models based on their theoretical ability to account for the light gradients and short light cycles experienced in well-mixed dense outdoor cultures. Type I models were defined as models predicting the rate of photosynthesis of the entire culture as a function of the incident or average light intensity reaching the culture. Type II models were defined as models computing productivity as the sum of local productivities within the cultivation broth (based on the light intensity locally experienced by individual cells) without consideration of short light cycles. Type III models were then defined as models considering the impacts of both light gradients and short light cycles. Whereas Type I models are easy to implement, they are theoretically not applicable to outdoor systems outside the range of experimental conditions used for their development. By contrast, Type III models offer significant refinement but the complexity of the inputs needed currently restricts their practical application. We therefore propose that Type II models currently offer the best compromise between accuracy and practicability for full scale engineering application. With respect to temperature, we defined as "coupled" and "uncoupled" models the approaches which account and do not account for the potential interdependence of light and temperature on the rate of photosynthesis, respectively. Due to the high number of coefficients of coupled models and the associated risk of overfitting, the recommended approach is uncoupled models. Most of models do not include the modeling of endogenous respiration, and light and temperature acclimation in spite of their potential effect on productivity.

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1. Introduction

Tremendous research efforts are currently ongoing to develop new algae biotechnologies for biofuel production (Chisti, 2007; Mata et al., 2010). However, the technical feasibility, economics, and environmental benefits of full-scale algal cultivation are still unproven and debated (Chisti, 2008; Guieysse et al., 2013; Murphy and Allen, 2011; Singh and Olsen, 2011). Of particular concern, many economic and life cycle assessments of algae cultivation are based on gross estimates of productivity that do not account for the impacts of process geometry (e.g. pond depth), operation (e.g. hydraulic retention time) and temperature on productivity (Béchet et al., 2010; Guieysse et al., 2013; Sánchez Mirón et al., 1999; Tredici and Materassi, 1992). There is therefore a critical need to accurately forecast algae productivity during outdoor cultivation in order to improve assessment of best location and engineering practice for maximizing revenues and minimizing environmental impacts.

Algal biomass productivity is the net result of photosynthesis and endogenous respiration (Box 1). Predicting the rate of these mechanisms during outdoor cultivation is challenging because algal activity is influenced by numerous factors such as light intensity, temperature, pH, dissolved oxygen concentration, and nutrient availability (Mata et al., 2010). In order to maximize the algal productivity per unit of land area, cultivation systems should ideally be limited by no other factor than the amount of light energy reaching the algae. Maintaining the pH at its optimal value can be done by CO_2 injection and nutrient concentration can be maintained at saturation (Grobbelaar, 2009). Concentration gradients can occur

Box 1
Definition of key concepts.

Endogenous respiration: Photosynthesis generates chemical energy in the form of ATP, NADPH, and organic material. Endogenous respiration includes the consumption of chemical energy at day time and the consumption of organic material at night time.
Algal productivity: Rate of net biomass production expressed as the difference of the rate of photosynthesis minus the rate of endogenous respiration.
Photosynthetic unit (PSU): Cell unit responsible for the photosynthetic process leading to the generation of ATP and NADPH (Camacho Rubio et al., 2003).
Light-inhibition: The degradation of key proteins at high light intensities causes a decrease of the rate of photosynthesis over time. For light-inhibition to become significant, algae cells must be exposed to inhibitive light intensities for a time period in the order of 1 min (Ferris and Christian, 1991). Light-inhibition can impact productivity past exposure to high light intensities because damaged cells need time to recover.
Light-acclimation: Change of cellular physiology and biochemistry associated with photosynthesis, such as the change of pigment content in the cell (Bernard, 2011; Crill, 1977; Sakshaug et al., 1991). Light-acclimation occurs on a timescale longer than light-inhibition and can take several hours to days to cause significant changes in pigment content (Crill, 1977).
Flashing-light effect: Following the capture of photons, the photosynthetic units (PSUs) of algae cells need approximately 100 ms to convert light energy into NADPH and ATP. During this time, any photon reaching 'excited' PSUs is wasted. As a result, cells exposed to flashing light with a light/dark cycle close to 100 ms waste less light energy than cells exposed to continuous light (Grobbelaar, 1991, 1994; Janssen et al., 2003; Luo and Al-Dahhan, 2004). The increase of photosynthetic efficiency resulting from cell exposure to flashing light is called the flashing-light effect.

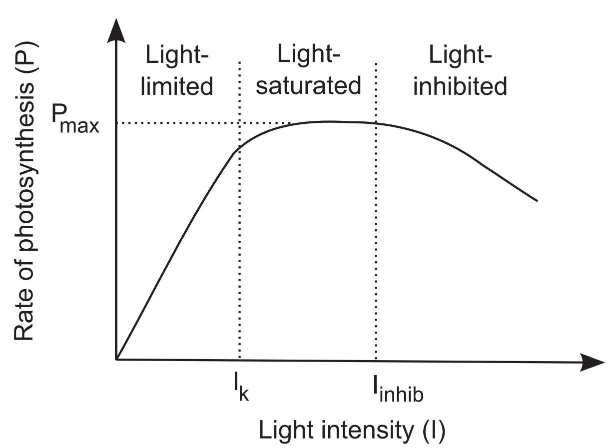

Fig. 1. Typical PI relationship showing the light-limited ($I < I_k$), light-saturated ($I_k < I < I_{inhib}$), and light-inhibited ($I > I_{inhib}$) regimes of microalgae light response.

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