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Hurdles and challenges for modelling and control of microalgae for CO_2 mitigation and biofuel production

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ABSTRACT

Oleaginous microalgae are considered to be a potential major biofuel producer in the future since, under conditions of nitrogen deprivation, they are capable of containing high amounts of lipids, while consuming industrial CO_2. These photosynthetic microorganisms are, however, rather different from the microorganisms usually used in biotechnology. In particular, predicting the behaviour of microalgal based processes is delicate because of the strong interaction between biology (microalgal development and respiration), and physics (light attenuation and hydrodynamics). This paper reviews existing models, and in particular the Droop model which has been widely used to predict microalgal behaviour under nutrient limitation. It details a model for raceways or planar photobioreactors, when both light and nutrients are limiting. The challenges and hurdles to improve microalgal culture process modelling and control in order to optimise biomass or biofuel production are then discussed.

1. Introduction

Autotrophic microalgae and cyanobacteria use photons as energy source to fix carbon dioxide (CO_2). These microorganisms (abusively called "microalgae") have recently received specific attention in the framework of renewable energy. Their high actual photosynthetic yield compared to terrestrial plants leads to large potential algal biomass productions of several tens of tonnes per hectare and per year [23]. After nitrogen starvation, this biomass can reach a very high lipid content (more than 60% of dry weight under certain stress conditions [75]). These possibilities have led some authors to consider microalgae as one of the main biofuel sources for the future [56,23,116].

In addition, the ability of microalgae to fix CO_2 in a controlled way has recently involved them in the race for mitigation systems [8,79]. Microalgal biofuel production systems could also contribute to mitigate industrial CO_2 emitted from power plants, cement plants, etc. In the same spirit, microalgae could be used to consume inorganic nitrogen and phosphorus in urban or industrial effluents, and thus limit expensive wastewater post-treatment [64].

Algal growth technologies for biofuel production and CO_2 mitigation were first developed from the mid-1970s to the mid 1990s in the framework of the Aquatic Species Program (ASP) funded by the US Department of Energy [100]. In Japan, the Research for Innovative Technology of the Earth program (RITE) from the New Energy Development Organization (NEDO) has carried out an extensive program in the 1990s for microalgal CO_2 utilisation, focusing on closed photobioreactors (PBR). These research activities reemerged at the worldwide scale at the end of 2000s, in the context of the strong increase of the oil barrel price, the critical necessity to secure energy supply and the clearer symptoms of the global climatic changes.

The advantages of microalgae put them in a good position for renewable energy production at large scale [23,116]. This explains the explosion of publications on this topic, and the optimistic claims of start-ups, which foresee, in the near future, industrial production of microalgal biofuel. However, microalgae have been so far only marginally used for biotechnological applications. To date, the main domains of application are focused on innovative processes to produce vitamins, proteins, cosmetics, and health foods [89,103]. Microalgae are grown in a broad range of Microalgae Culture Processes (MCP) ranging from rudimentary open ponds to high technology closed photobioreactors. They are, however, still cultivated at small scale: the total worldwide microalgal production is in the range of 10 000 tonnes of dry biomass per year to be compared to 105 million m^3 of biofuel (biodiesel and bioethanol) worldwide produced in 2010 [43].

In the perspective of large scale microalgal cultivation, new techniques both from biotechnology and from the control field

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