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The effect of photon flux density on algal biofilm growth and internal fatty acid concentrations

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ABSTRACT

Algal biofilm systems offer potential advantages over planktonic systems for growing, harvesting and processing algal biomass. To determine how feasible these systems can be, however, researchers must determine optimal biomass and lipid productivities. In this paper the effect of photon flux density (PFD) on algal biofilm biomass productivities, internal fatty acid concentrations, and overall fatty acid productivity was studied. It was determined that as PFD increased, algal biofilm biomass productivities significantly increased until they peaked i.e. at about 300 μmol/m^2/s, presumably due to light saturation. Increasing PFDs from 50 to 150 μmol/m^2/s produced statistically significant increases in fatty acid concentrations from 5% to 8%; however, increasing PFDs beyond that range did not enhance lipid accumulation. Because of significant increases in biomass productivity with increased PFD, there was also a significant increase in fatty acid productivity with increased PFD. Lastly, increasing PFD resulted in diminishing returns of biomass productivity, suggesting that photons are not being effectively utilized at higher light intensities. This finding has implications for photobioreactor design and operation with artificial lighting.

1. Introduction

The production of biofuels and biochemicals from algae biomass has become a highly researched topic over the past several decades for many reasons. Due to their high growth rates and high internal lipid concentrations, many algal species have the potential to outproduce conventional terrestrial crops in terms of biomass and biofuel productivity per area of land [9,32]. Algal growth systems do not require the use of arable lands and so do not compete with food production. These systems can also utilize municipal wastewater streams as a source of nitrogen and phosphorous compounds essential to growth, and industrial flue gas streams as an abundant source of CO_2 for photoautotrophic metabolism. Use of these waste streams as nutrient sources remediates the waste, reduces the overall cost of algal biomass production and, may add revenues when considering carbon taxes and wastewater treatment service fees. Although the production of biofuels and biochemicals from algal cultures has great promise, there are still many technical hurdles to overcome before it is commercially viable.

One of the greatest technical challenges of economically producing biofuels and biochemicals from algal biomass is harvesting, de-watering and concentrating the dilute biomass [16,46]. Gudin and Therpenier [17] estimate that this cost represents about 20–30% of the production of the biomass when algae are grown planktonically. Because of this, there is increased interest in growing algal biomass as a biofilm, rather than in the conventional planktonic state. Algal biofilms offer potential advantages over planktonic algal growth systems because they are immobilized and highly concentrated – 10–16% (*w*/w) solids [10,37] – by nature, rendering them potentially more economically harvestable. Christenson and Sims [10] demonstrated that algal biofilm biomass is naturally as concentrated as planktonic biomass after de-watering by centrifugation, and 2–15 times more concentrated than planktonic biomass after sedimentation and dissolved air flotation. Moreover, due to their immobilized nature, biofilms offer advantages over planktonic systems for wastewater treatment because it is naturally separated from the bulk liquid medium.

Another potential limitation to growing algae for fuels and chemicals is the utility costs (capital and operational) associated with the use of ponds and photobioreactors (PBRs). Although most researchers agree that fuels and low value chemicals can only be economically grown using natural (sun)light [2], weather conditions and seasonal sunlight and diurnal variations may require the use of artificial light supplementation to maximize biomass production and limit carbon loss from cellular respiration [4,7,36]. However, the economics of using artificial lighting become more favorable when producing high value products.

Abbreviations: FAME, Fatty acid methyl ester; PAR, Photosynthetically active radiation; PBR, Photobioreactor; LED, Light emitting diode; EPS, Extracellular polymeric substances; CPCC, Canadian Phycological Culture Centre; PFD, Photon flux density.

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In algal growth systems using artificial lighting, there is an apparent advantage to using only red light emitting diodes (LEDs) as the light source, as suggested by Blanken et al. [4]. There are several reasons for this: 1) red LED light outperforms all other colors of light, including white, when considering biomass productivities in planktonic systems [48]; 2) red LED light significantly outperforms all other colors of light, including white, when considering energy efficiencies of (planktonic algae) biomass conversion from electrical energy inputs i.e. it takes less electrical energy to produce red light photons [4,48]; 3) LED wavelength bandwidths can be controlled and are well defined; 4) compared to other light sources, LEDs have long lifespans and their intensities and bandwidths do not fade or drift as they age; 5) LEDs are small compared to other artificial light sources, making their integration into PBRs relatively easy; and 6) LEDs do not emit infrared radiation, which can be a source of excess heat in algal growth systems. In addition, recent studies have demonstrated that algal biofilms, like their planktonic counterparts, grow well under red light only conditions [15,40,41].

It is well known that the amount of photosynthetically active light supplied to algal cells significantly affects algal growth. Many researchers have shown that increasing photon flux density (PFD) significantly increases the growth rate and maximum cell density in planktonic algal growth systems, but beyond certain maximum tolerable PFDs, these cultures can become photoinhibited and/or photooxidized [13,43,48,49]. There is some evidence that suggests similar phenomena exist with algal biofilms. For instance, Liu et al. [31] observed incremental increases in algal biofilm biomass productivity when PFDs of photosynthetically active radiation (PAR) were incrementally increased; however, they concluded that a light saturation point was met above 150 μmol/m^2/s (PAR), resulting in smaller growth rate increases with increases of PFDs. Similarly, Kebede-Westhead et al. [27] increased PFDs from 270 to 390 μmol/m^2/s, resulting in biomass productivity increases of 14.8 to 17.2 g/m^2/d, respectively. Lastly, many studies have demonstrated that increasing PFDs significantly increases overall photosynthetic activity (measured as oxygen evolution) in thick algal biofilms, and that the depth of photosynthetic activity is correlated to PFD [3,14,25,30]. It is reasonable to assume that photosynthetic oxygen production is correlated to growth and biomass production. Although some researchers have also demonstrated a correlation between PFD and increased algal biofilm growth rates [27,31], most have not explicitly tested this relationship through a broad range of PFDs.

In addition to affecting growth kinetics, there is some evidence that PFD affects internal lipid concentrations of algae grown planktonically. For instance, Wang et al. [49] found that total lipid content increased from 12% to 35% (*w*/w) when PFDs were increased from 50 to 1200 μmol/m^2/s (PAR). Similarly, Rodolfi et al. [38] and Solovchenko et al. [44] demonstrated significant increases in fatty acid content in planktonic algae with increased PFD. To the best of our knowledge, however, there is no information on the effect of varying PFDs on the lipid content of algae grown as an immobilized biofilm. Because biomass lipid concentration and biomass growth rate are major contributors to overall biofuel and biochemical productivity, it is very important to understand the effect of light on lipid yield within algal biofilm biomass. This is particularly relevant since, under certain circumstances, algal biofilms respond very differently to environmental change compared to their planktonic counterparts [40].

Biofuel and biochemical production from algal biofilm research is still in its infancy. In order to understand its economic and social potential, it is important that we understand its potential for overall productivity – in terms of biomass growth rates and internal biocompound concentrations – and the way it responds to environmental change. In this paper we examine the effect of various PFDs on algal biofilm biomass productivities, total biomass yields, and internal fatty acid concentrations in order to test the hypothesis that increasing red light PFDs increases yields and productivities.

2. Materials and methods

An algal biofilm growth system was designed to characterize and control the main parameters affecting algal biofilm growth rates. The system also allowed for large and controllable ranges of photon flux density to test the effect of light on algal biofilm growth and internal fatty acid concentrations. Replicate sampling from this system facilitated the collection of growth kinetics and internal fatty acid concentration data from the biofilms.

2.1. Biofilm growth system

The design and operation of this algal biofilm growth system (Fig. 1) is similar to the one outlined in Schnurr et al. [40]. It is a semi-continuous flat plate parallel horizontal photobioreactor (PBR) with approximately 95% (*v*/v) re-circulation and approximately 5% fresh

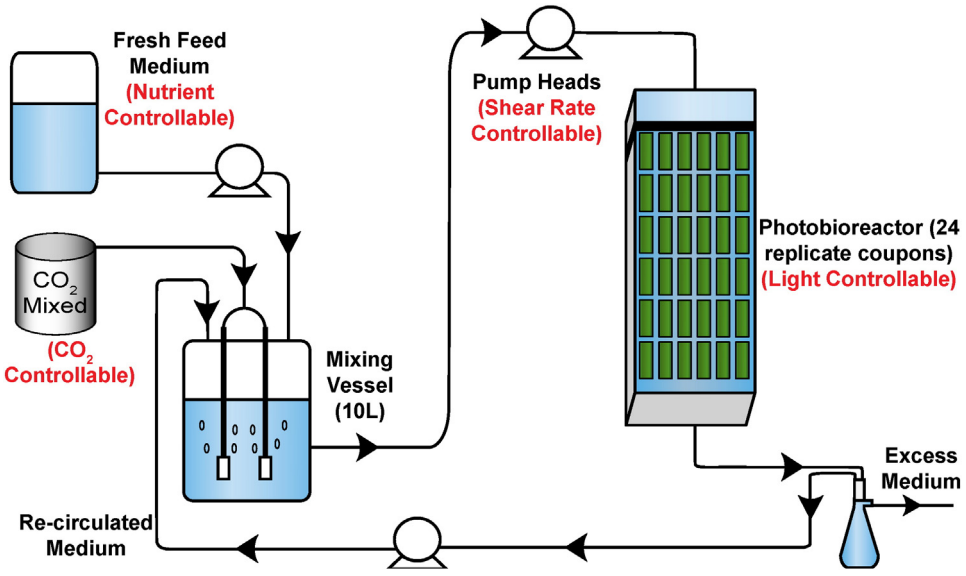

Fig. 1. Schematic diagram of the algal biofilm culturing system used to study the effects of photon flux density on algal biofilm growth kinetics and internal lipid concentrations.