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Growth rates and photon efficiency of *Chlorella vulgaris* in relation to photon absorption rates under different LED-types

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ABSTRACT

A general model was developed that depicts the long-term growth profiles of *Chlorella vulgaris* batch cultures under different light intensities of white LED light. The model equation reflects the growth with a time delay of second order at different light intensities by changing only one parameter of the entire equation. This model was applied to the data of short-term batch cultures at different incident light intensities of white, blue, green and red LEDs and growth rates were calculated. Models for the growth rates depending on the photon absorption rates for the different LED-types were developed. Photon absorption rates can be determined for other photobioreactor systems, hence the growth rates of *Chlorella vulgaris* in other reactor systems can be calculated using the newly developed models. At photon absorption rates up to 2.5 Einstein L^{-1} d^{-1}, *C. vulgaris* yielded the highest growth rates under red LEDs. At higher photon absorption rates, white light led to the highest growth rates. Green and blue LEDs yielded similar growth rates which were consistently lower than the growth rates under white and red LEDs. Maximum photon efficiency of ~130 absorbed photons per fixed CO_2 was reached under red LEDs.

1. Introduction

The proportion of marine phytoplankton in global photosynthetic biomass production is about 50%, which corresponds to a fixation of more than 48 billion tons of atmospheric carbon in the form of CO_2 [1]. Microalgae are the basis of all aquatic food chains and thus indirectly also part of the human food chain. Microalgae, therefore, can be regarded as enormously important organisms for the global ecosystem.

Due to their valuable nutrient composition (including high protein content, many long-chain-, unsaturated fatty acids), microalgae can also be utilized directly as a food source for humans. NASA describes microalgae as an excellent, compact food for astronauts. Microalgae are also widely used as feedstuffs in animal husbandry: concentrated feed for poultry, ruminants, and pigs can be replaced by microalgae [2]. In aquaculture of fish, shrimp, mollusks and crustaceans, microalgae are irreplaceable as aquatic food chains start with microalgae [3,4]. Further applications of microalgae due to their high nutrient content are cosmetics, food supplements, and pharmaceutical products. In these areas, a very high profit can be realized in relation to the produced biomass [5].

The subject of intensive research is the generation of energy on the basis of microalgae. There is a consensus that the use of fossil fuels is not sustainable due to running out of resources and accumulation of greenhouse gases in the atmosphere [6]. Various methods exist for converting untreated algae biomass into liquid, gaseous and solid fuels [7].

Abbreviations: $A_{culture}$, exposed surface area of the algae suspension in the photobioreactor (m^2); Abs_{LED}, absorption of light by the algae suspension of the corresponding LED type (−); $Abs_{culture,LED}$, fraction of incident *PFD* of the corresponding LED type in the photobioreactors that was actually absorbed by the algae cells (−); *C*, biomass (i.e. dry matter) concentration of the algae suspension (g L^{-1}); C_{prod}, photosynthetically produced net biomass (g L^{-1}); *d*, cultivation time (d); *df*, dilution factor = volume of the measured sample divided by the volume of the extracted culture suspension (−); *D*, internal diameter of the photobioreactor tube (cm); E, Einstein = 1 mol photons (mol); *h*, height of measuring point in a reactor tube (cm); OD_{850}, optical density at 850 nm (−); *PFD*, photon flux density (E m^{-2} s^{-1}); PFD_{LED}, measured *PFD* of the corresponding LED-type in a reactor tube (E m^{-2} s^{-1}); $PFD_{in,LED}$, average incident *PFD* of the corresponding LED-type in a photobioreactor (E m^{-2} s^{-1}); $PFD_{refl,LED}$, fraction of transmitted light through the reactor tube that was reflected (at the reflective film the reactor housing was lined with) back into the reactor tube (−); RPA_{LED}, photon absorption rate of the light of the corresponding LED type by the algae culture in the photobioreactor (E L^{-1} d^{-1}); *s*, layer thickness (cm); *S*, saturation value for the produced biomass to which the cultures approach with time (g L^{-1}); T_1,T_2, time constants of the PT_2-element (−); Tr_{LED}, Transmission of light of the corresponding LED type by the algae suspension (−); $V_{culture}$, volume of the algae suspension (L); w_{LED}, growth rate under the corresponding LED-type (g L^{-1} d^{-1})

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Microalgae show significantly higher growth rates than land plants. Each algae cell is photosynthetically active, nutrients and CO_2 can be absorbed directly from the surrounding medium and used in photosynthesis to build further biomass and form new cells. Algae biomass can be harvested daily, hourly or even continuously, while land plants can often be harvested only once per year [8].

In order to benefit from the advantages of microalgae, production of algae biomass has to be more cost-effective and more efficient. A better understanding of the biophotonic processes and the effect of different light conditions on the photosynthetic performance of the algae are therefore absolutely necessary.

In literature, various approaches do exist to model the growth of microalgae depending on light conditions. Both growth and light conditions are defined differently. For example, the O_2 release rate was modeled according to varying photon flux densities (*PFD*s) entering the reactor [9], the specific growth rate was modeled depending on the average *PFD* in the reactor and the accumulated local growth rates were modeled depending on local photon absorption rates [10].

Incident *PFD* does not take into account the geometry of a reactor or light absorption of algal cells [11]. Therefore, modeling algal growth relative to the *PFD* entering a reactor is unsuited to describe productivity of microalgae cultures in photobioreactors. In other models, growth rate is related to the average *PFD* inside a reactor [10,12–14], since, in well-mixed systems, each algae cell is exposed to the same light intensity and achieves the same rate of photosynthesis. However, average *PFD* inside a reactor is directly dependent on the biomass content of the algae suspension. In many studies, the basis for calculation of average light intensities or light attenuation with respect to the biomass content of the algae suspension, is Lambert-Beers' law, in which a constant absorption coefficient for the algae biomass is assumed.

Other studies have shown that this is not correct by specific absorption properties of the algae and in particular by application of different light spectra [15,16]. A further variant is modeling growth depending on the number of actually absorbed photons. This is advantageous since specific absorption properties of algal cells have to be taken into account and are particularly important when the influence of different light spectra is to be investigated. Schreiber et al. [17] reported significant differences in the electron transport rate, depending on whether they were related to incident or absorbed *PFD*. Therefore, in order to study the wavelength-specific photosynthetic performance of organisms with wavelength-specific absorption, a measuring unit should be used that describes the number of absorbed or converted photons per time [18]. Theoretically, the absolute maximum performance of carbon fixation is 8 mol absorbed photons per fixed mole of CO_2 via photosynthetic linear electron transport. Fixation of one CO_2 in the Calvin cycle requires two NADPH from the linear electron transport chain. Four photons are required (two in Photosystem I and II, respectively) to provide four electrons for the formation of one NADPH. A photon efficiency of eight absorbed photons per fixed CO_2 will never be reached, since, amongst other things, not every absorbed photon exclusively drives linear electron transport, not every NADPH drives the Calvin cycle and not every fixed CO_2 remains unaffected for the accumulation of further biomass [19–21].

Algae growth was frequently defined by the increase in cell count per culture volume. However, cell size is proportional to cell weight and varies with different light spectra [22] and also depends on cultivation time [23]. Therefore, cell number itself is not suitable as a measure for algae growth or photosynthetic performance.

To date, no comprehensive studies have been conducted in which growth rates of the green alga *Chlorella vulgaris* in photobioreactors have been modeled depending on photon absorption rates of both quantitatively and qualitatively different light intensities.

2. Objective

The aim of this work is to model the growth rates of *C. vulgaris* in regard to photon absorption rates under different light spectra. First, a general growth model for the long-term profile of biomass content in batch cultures has to be developed by means of long-term experiments at different light intensities under white LED light. The resulting model should be applied to a series of short-term batch experiments under white, blue, green and red LED light at different light intensities and constant heat properties. During all experiments, light is said to be the only limiting factor of algae growth. Subsequently, a model for the growth rates ($g\,L^{-1}\,d^{-1}$, model output) of *C. vulgaris* in regard to photon absorption rates ($E\,L^{-1}\,d^{-1}$, model input) is to be established. The photon efficiency is to be calculated and expressed as absorbed photons per fixed CO_2 for each light spectrum used.

3. Materials and methods

3.1. Culture conditions

The photobioreactor system used consisted of ten bubble-column reactor tubes made of glass with a diameter of approx. 65 mm and a capacity of 1.26 L (Fig. 1). The lighting system consisted of various high-power LEDs (cool- white, blue (both from Philips, Amsterdam, NL), green and red (both from Roithner Lasertechnik, Vienna, AUT), emission spectra in Fig. 2). All surfaces within the reactor housing facing the reactor tubes were lined with a reflective film (reflection spectrum in Fig. 2) in order to increase light intensities inside the tubes at identical light emissions of the LEDs. The light period was 16 h per day.

Light was supplied by at least 6 and up to 36 LEDs evenly distributed around the reactor housing. Light intensities were adjusted to values between 20 and 1430 $\mu E\,m^{-2}\,s^{-1}$. Aeration rate was 0.4 L per minute and liter of algae suspension. The CO_2 content of aeration gas was kept constant at 2% by volume. The temperature of the culture

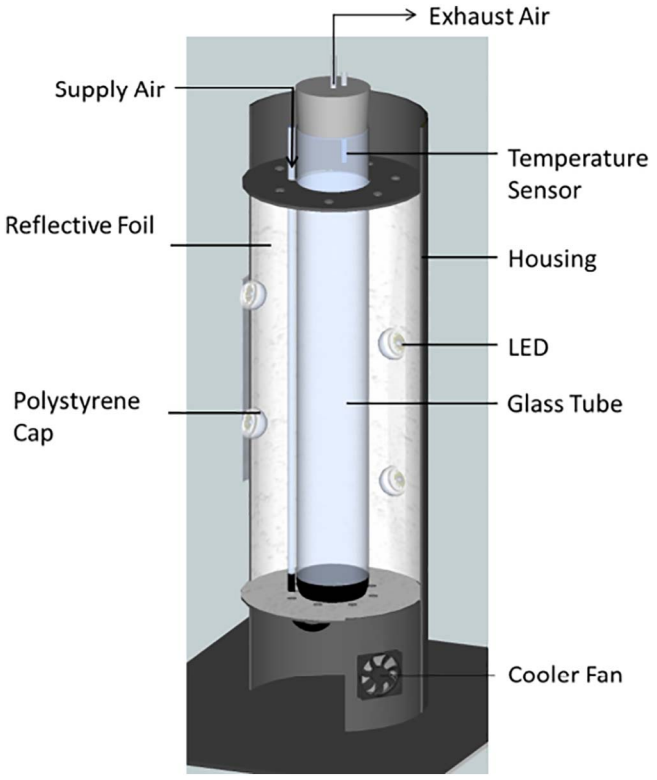

Fig. 1. Sketch of one photobioreactor used.