Algal Research 29 (2018) 354–360

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

Empirical operating strategy to reduce the light-specific energy consumption of a flat-panel airlift photobioreactor with intrinsic static mixers cultivating *Thermosynechococcus elongatus* BP-1☆

Peter Bergmann[a,*], Walter Trösch[b]

[a] Subitec GmbH, Julius-Hölder-Str. 36, 70597 Stuttgart, Germany
[b] University of Hohenheim, Institute of Food Science and Biotechnology, Garbenstraße 25, 70599 Stuttgart, Germany

ARTICLE INFO

Keywords:
Flat-panel airlift photobioreactor
Intrinsic static mixers
Light utilization
Specific energy consumption
Automation
Outdoor

ABSTRACT

During photoautotrophic cultivations using optimized synthetic media, light is the limiting "substrate" of high-density cultures, especially throughout outdoor cultivations prohibiting adjustment of photon-flux density (PFD). Convective mass transfer (turbulence) is the method of choice to cope with that limiting effect. Then again, turbulence comes at costs through the energy required for its generation. In this context and based on laboratory data generated with *Thermosynechococcus elongatus* BP-1, an empiric operating strategy for flat-panel airlift photobioreactors with intrinsic static mixers is suggested. Repeated cultivations were performed from sub- to supra-saturating PFD (180 to 780 μmol m^{-2} s^{-1}) at aeration rates ranging from 0.11 to 0.83 vvm assessing the cultures' productivities along the courses of biomass concentrations. The results indicate that, owing to the culture-flow directing mixers, there is a strong interrelation between the effects of PFD, biomass concentration and aeration rate (thus energy input) applied. Hereby, the positive impact of directed turbulence on the cultures' performance with respect to productivity and yield was greatest at high biomass concentration ($> 5\ g_{DW}\ L^{-1}$) and PFDs with effects becoming less dominant while the latter two were reduced. Based on the quantitative findings and utilizing the easily monitored parameters PFD and biomass concentration, a computational model may be defined automatically controlling the easily adjustable parameter aeration rate. Without a negative influence on cultures' performance, this will allow for both, increase of culture performance at times of intense light and high biomass concentration as well as reduction of operational expenditures (OPEX) at times of dim light or low biomass concentration. Compared to the standard, continuous aeration regime, this may lead to a reduction of energy required for the generation of turbulence of 37%, especially when considering outdoor cultivations in temperate climate zones.

1. Introduction

Worldwide, microalgae are investigated as potential candidates to positively impact global challenges such as the supply of food [1], feed [2], bulk chemicals [3] and even biofuels [4] since decades [5]. Nevertheless, for the time being microalgae derived and commercially available products are, besides the utilization of *Chlorella* and *Arthrospira* (*Spirulina*) biomass as nutraceuticals, restricted to only a few high added-value products (HAVs) [6]. Besides regulatory obstacles for the introduction of novel HAVs such as antimicrobial agents [7], introduction and market penetration of these products is restricted by the currently high production costs of microalgal biomass, either associated to downstream operations, i.e. de-watering of low-density cultures, or actual operational expenditures of cultivation in closed photobioreactors (PBRs) [8]. In low-cost open systems, numbers of microalgae species to be cultivated is limited by their ability to withstand extreme environments, i.e. high salinity or pH value, while decreasing the number of potential contaminants [9]. Although measures of pest control are under continuous examination [10], their economically viable implementation on industrial scale is yet to be proven for mesophilic strains. Therefore, PBRs are considered that, besides the reduced risk of contamination, allow for streamlined process control, ultimately resulting in maximized growth rates and biomass concentrations [9]. Hereby, PBR performance and thus growth rate is

☆ Previous submission to Algal Research:
Bergmann, P. and Trösch, W. (2016): Repeated fed-batch cultivation of *Thermosynechococcus elongatus* BP-1 in flat-panel airlift photobioreactors with static mixers for improved light utilization: Influence of nitrate, carbon supply and photobioreactor design. Algal Research (17), pp. 79-86.

* Corresponding author.
E-mail address: p.bergmann@subitec.com (P. Bergmann).

https://doi.org/10.1016/j.algal.2017.10.014
Received 22 March 2017; Received in revised form 21 October 2017; Accepted 21 October 2017
Available online 22 November 2017

determined by the interplay of hydrodynamics and light distribution [11], inevitably confronting a light gradient through the PBR resulting from mutual shading of the cells in dependence of the prevailing PFD and cell density. Fluid turbulence is known to contribute to algal proliferation as it keeps cells in suspension, eliminates thermal stratification and allows for homogeneous nutrient distribution [12]. In addition, turbulence results in constant reallocation of photosynthetic cells through the PBR's photic zones, from the dimly lit or rather completely dark interior to the illuminated PBR surface often characterized by excessive light availability. By inducing these light/dark (L/D) cycles, microalgal growth is supported [13]. Hereby, productivity increases along with increasing frequency of the L/D cycle [14]. Novel PBR geometries therefore aim towards the induction of frequent L/D cycles by the incorporation of static mixers [15,16,17] and their implementation was shown to have significant positive effects on growth rate and final biomass concentration [18]. Although these installations efficiently increase solar conversion efficiency by at least partially overcoming the inhibitive effects predominant in only randomly mixed cultures (photoinhibition and photolimitation), the generation of turbulence remains one of the main costs drivers in microalgal biotechnology contributing to overall biomass production costs. This is especially true when using closed PBR systems [19] for which production costs from around 5 € kg^{-1} [19], over 69 € kg^{-1} [20] to even US$ 400 kg^{-1} [21] are reported in literature. On the contrary, production costs well below 1 € kg^{-1} dry weight are aspired for bulk application of microalgal biomass [22]. Therefore, any attempt targeting the reduction of operational expenditures is relevant.

The present study aimed towards generating an insight into the complex interplay between hydrodynamics and light distribution when cultivating the thermophilic cyanobacterium *Thermosynechococcus elongatus* BP-1 in a flat-panel airlift photobioreactor with intrinsic static mixers (FPA-PBR) [18]. Ultimately, the study aimed towards the development of the groundwork for an advanced control-command strategy enabling an automated adjustment of the aeration rate (turbulence) in dependence of the prevailing PFD and biomass concentration, thus reducing the light-specific energy input during microalgal cultivation. Light is the most crucial factor in microalgal mass production. As solar PFD undergoes natural diurnal and seasonal variations between 0 and 2000 µmol $m^{-2} s^{-1}$ in the PAR (photosynthetically active radiation) region, both phenomena, photolimitation (e.g. dense culture and/or dim light) [23] and photoinhibition (e.g. low density cultures and/or excess light) [24,25] can minimize productivity and even irreversibly damage algal cultures [26]. It is therefore necessary to adapt cultures' hydrodynamics with respect to these changing conditions to maximize productivity and/or minimize energy demand for culture mixing. Intermittent aeration over the nighttime has already been studied and showed that a significant decrease of 45% in aeration (and thus energy demand) is possible without influencing algal growth [27]. Here, a pursuing strategy for FPA-PBR operation over the course of the day is suggested.

2. Material and methods

2.1. Organism and medium

2.1.1. Organism

Thermosynechococcus elongatus BP-1 was kindly supplied by the Humboldt Universität zu Berlin, Berlin, Germany. Directly upon receipt, cultures were up-scaled and transferred to culture maintenance serving as inocula for experiments as described in [18].

2.1.2. Medium

Performed cultivations used the inorganic BG 11 prepared in deionized water and modified from Rippka and Herdmann [28] applying the micronutrient solution from Kuhl and Lorenzen [29] in accordance to the medium recipe stated by the Culture Collection of Algae at Goettingen University (SAG). During culture maintenance and PBR cultivations, medium was used at threefold the standard concentration allowing for rapid cell proliferation to high densities. Based on previous findings [18], medium was supplemented to contain (in mg L^{-1}) NO_3, 2000; PO_4, 200. and Na_2CO_3, 40. All chemicals used were of analytical grade.

2.2. Analytics

2.2.1. Optical density

Optical density (OD_{750}) was determined using a tabletop spectrophotometer (type DR 3900, Hach Lange GmbH, Berlin, Germany). Measurements were performed in triplicates against deionized water. Samples were diluted with deionized water to result in an OD_{750} between 0.1 and 0.4 during measurements.

2.2.2. Dry weight

Dry weight (DW) was determined by identifying the difference in weight of pre-weight aluminium bowls following the addition of cyanobacterial suspension and successive drying to constant weight at 105 °C as described previously [18]. Correlation between DW and OD_{750} was performed using the linear fitting function of the software OriginPro (v9.1, OriginLab Corp., Northampton, USA) (see Eq. 1).

$$DW\ [g\ L^{-1}] = 0.277^{*}\ OD_{750} \quad (R^2 = 0.999, N = 9) \tag{1}$$

2.2.3. Light Source and photon-flux density

High pressure sodium-vapor (HPS) lamps were used. Photon-flux density (PFD) was determined in the PAR region using a mobile quantum sensor (type LI-190, LI-COR, Inc., Nebraska, USA) and light meter (type: LI-250A, LI-COR, Inc., Nebraska, USA). PFD was measured at 10 points evenly distributed over the FPA-PBR's surface and averaged. PFD was adjusted according to the scientific question under examination.

2.2.4. Nutrient concentration

Concentrations of nitrogen and phosphorus were monitored daily throughout the FPA-PBR experiments and re-fed if necessary. Therefore, samples were centrifuged and respective concentration measured in the resulting supernatant using quantitative colorimetric cuvette tests as previously described [18]. Nutrients were re-fed by sterile filtration.

2.3. Photobioreactor design and operation

2.3.1. Geometry and functionality

The PBR operated during the experiments represents a FPA-PBR with integrated flow directing static mixers (horizontal culture flow) and downcomer domains (vertical culture flow, loop principle) (see Fig. 1). The reactor was initially developed, patented [30,31] and described [32,33] by the Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB (IGB), Stuttgart, Germany, and is now commercialized by Subitec GmbH, Stuttgart, Germany. The most distinctive feature of the FPA-PBR are the incorporated static mixers allowing for a controlled movement of microalgal cells from the illuminated surface area to the dimly lit interior of the PBR. Hereby, negative effects of photoinhibition and photolimitation are reduced by intermittent exposure towards the excess light at the PBR's surface versus the insufficiently illuminated interior. Frequency of cycling can be adjusted by the aeration rate applied. The design of the reactor and utilized peripherals as well as procedures of initiating experiments are extensively described by Bergmann *et al.* [18]. The present work focused on the interaction of the PFD and aeration rate applied and their mutual influence on cyanobacterial growth kinetics (productivity and biomass concentration). Therefore, PFD and aeration rate were varied over the course of the experiments between 180 and 780 µmol $m^{-2} s^{-1}$ and 40