Algal Research 25 (2017) 381–390

Contents lists available at ScienceDirect

Algal Research

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

Open thin-layer cascade reactors for saline microalgae production evaluated in a physically simulated Mediterranean summer climate

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ARTICLE INFO

Keywords:
Open thin-layer cascade photobioreactor
LED-based climate simulation
Nannochloropsis salina
Pilot-scale batch cultivation
Economic bioprocess metrics

ABSTRACT

While microalgae hold the promise for conversion of sunlight and CO_2 to a wide variety of products, the economics of algae processes are still debatable. We have designed an open thin-layer cascade photobioreactor for high-cell density cultivation of saline microalgae to advance economic microalgae mass production. Pilot-scale reactors with a surface area of up to 8 m^2 (cultivation volume 50–140 L) were constructed and evaluated using a dynamic climate simulation technology (light, air temperature and humidity) integrating natural sunlight and multi-color LED arrays for a highly realistic reproduction of the sunlight spectrum. Batch processes with *Nannochloropsis salina* were performed in these reactors in the physically simulated Mediterranean summer climate of Almería, Spain – an ideal location for outdoor microalgae cultivation. Two reactor variants were examined: one with a smooth but expensive rigid channel made of polyethylene sheets, and one with a more uneven but significantly less expensive channel made of pond liner. Maximal intra-day growth rates of 1.9 d^{-1} were observed at a cell density of 1–3 g L^{-1}. The maximal cell density of 50 g L^{-1} was obtained within 25 days. These high growth rates and cell densities markedly exceed literature data. No difference in growth between the channel variants was observed. This suggests that cost-efficient large-scale thin-layer cascade reactors with inexpensive pond liner channels are feasible. The high cell density allows a reduction of harvesting cost. Optimal process conditions were identified by analyzing the batch and daily economic bioprocess metrics: At a cell density of 17 g L^{-1}, an areal biomass productivity of 25 g m^{-2} d^{-1} (volumetric productivity 4 g L^{-1} d^{-1}) and a photosynthetic conversion efficiency of 4.6% were observed. The reactor design is discussed in detail to encourage further advancement of thin-layer algal cultivation technology.

1. Introduction

Outdoor mass production of microalgae is poised to impact renewable bio-production of food, chemicals and energy [1]. Algae cultivation is sustainable as it does not compete with agricultural activities and can utilize salt- or waste water, thereby circumventing depletion of valuable fresh water resources [2]. At present, only few high-value industrial products such as pigments are generated by outdoor microalgae processes. For low-value bulk chemicals or biofuels, production cost are currently too high to provide economic viability [3].

The choice of a cultivation system has a major effect on production cost. Open cultivation systems are suitable to generate low-value products [4–6]. The most widely used open cultivation system is the raceway pond. However, with its depth of 15–30 cm, low cell densities of only 1–1.5 g L^{-1} are achieved [7–9]. Hence, energy costs for circulation and harvesting of the algae are high and the cultures are susceptible to contamination [10,11]. A promising alternative is the thin-layer cultivation concept pioneered in Třeboň, Czech Republic [12–14]. This bioreactor concept provides for a microalgae suspension to flow down a sloped channel in a layer of < 1 cm thickness. At the end of the channel, the suspension is pumped up again to the starting point. High cell densities of 30–50 g L^{-1} after 2–3 weeks have been reported in

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Abbreviations: CDW, cell dry weight; LED, light-emitting diode; PAR, photosynthetically active radiation; PPFD, photosynthetic photon flux density; TUM, Technical University of Munich

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http://dx.doi.org/10.1016/j.algal.2017.06.004
Received 3 March 2017; Received in revised form 9 May 2017; Accepted 8 June 2017
2211-9264/

outdoor cultivation of *Chlorella* and *Scenedesmus* freshwater strains in the Czech Republic and Greece [15–17]. Moreover, the microalgae production cost in thin-layer systems were estimated to be only 20% of the cost in raceway ponds [11].

Unfortunately, technical information on thin-layer cascade reactors is scarce [11,12,18] and a detailed functional evaluation of all reactor parts is not available, hampering the advancement of thin-layer cultivation. Furthermore, a comparison of different reactor setups is difficult because precise intra-day growth rates have not been determined yet. Moreover, no thin-layer cascades for saltwater have been developed yet, although saline cultivation is desirable because of reduced freshwater use and contamination risk as well as improved CO_2 containment in the aqueous phase due to higher pH. Finally, the channels of published thin-layer cascade reactors were made from expensive rigid materials like steel, glass, concrete or fiberglass [19,20], resulting in a high investment cost compared to other open cultivation systems. Thus, the development of thin-layer cascade reactors addressing these issues appears to be a valuable addition to the growing field of microalgae research.

Testing bioreactors and processes on a larger scale usually requires outdoor experiments. However, achieving a thorough understanding of an outdoor process is complicated by randomly changing environmental conditions. A solution to this is physical and dynamic day and night climate simulation – the realistic indoor reproduction of outdoor environmental conditions [8,21]. With the recent advent of light-emitting diode (LED) technology in microalgae research [22], faithful sunlight simulation has become possible. Experiments under controlled environmental conditions allow informed decisions on worthwhile improvements. The development process is accelerated since the experiments are independent of outdoor weather conditions. As a result, the investment for a large-scale outdoor microalgae production facility will more likely be profitable if the process has been thoroughly tested and optimized indoors under the environmental conditions of the envisaged outdoor site.

This paper reports on the design, construction, operation, and evaluation of open thin-layer cascade photobioreactors at TUM AlgaeTec Center (Technical University of Munich, Germany), a microalgae research facility enabling physical and dynamic day and night climate simulation on a pilot scale. The LED-supported climate simulation system is presented and the thin-layer cascade reactor design is discussed. The saline microalga *Nannochloropsis salina* was chosen as a model to evaluate batch process performance in open thin-layer cascade photobioreactors with a surface area of up to 8 m^2. In these processes, the climate simulation reproduced the environmental conditions of a Mediterranean summer in Almería, Spain, a suitable location for a large-scale outdoor microalgae cultivation site.

2. Materials and methods

2.1. Open thin-layer cascade photobioreactor

The thin-layer cascade reactor design developed and used in this study (Fig. 1) consisted of five modular reactor parts: inlet module, upper channel, flow reversal module, lower channel, and retention tank (parts given in order of the flow of the algae suspension). A detailed technical description of the reactor parts is given in the Supplementary materials.

An off-the-shelf centrifugal pump was used to lift the algae suspension from the retention tank to the inlet module, reducing investment and operational cost compared to raceway ponds where custom-engineered paddlewheels are required. In the pilot-scale implementations of this reactor design, the channel width was fixed to 1 m and the channel length was varied. In total, two reactors of 4 m^2 each and six reactors of 8 m^2 each were constructed.

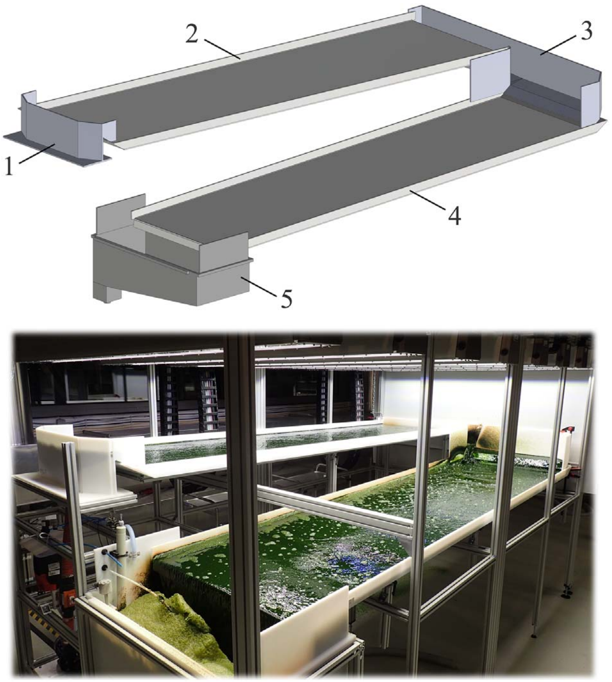

Fig. 1. The open thin-layer cascade photobioreactor developed and used in this study (3D CAD drawing and photo). 1 inlet module, 2 upper channel, 3 flow reversal module, 4 lower channel, 5 retention tank. The photo shows a small volume of foam in the retention tank. No anti-foaming agent was required because of the mechanical foam destruction inherent in the reactor design: the accumulating foam was continuously destroyed by the algae suspension falling from the lower channel into the retention tank.

The reactor was designed to be modular (the geometry is easily modifiable), automated (after inoculation the bioprocess can run for weeks without manual intervention, and detailed bioprocess data is automatically acquired), easily cleanable, and corrosion-resistant. The reactor modules (inlet module, flow reversal module, retention tank) were made of white high-density polyethylene (manufactured by Rauch, Feldkirchen, Germany). Two channel types were examined. An initial design involved a very smooth but expensive rigid channel made of white high-density polyethylene sheets (10 mm thickness, Rauch, Feldkirchen, Germany). A significantly less expensive design encompassed a slightly more uneven pond liner channel made of white woven coated polyethylene fabric (areal weight 320 $g\,m^{-2}$, Daedler, Trittau, Germany) placed on galvanized welded steel wire mesh (wire diameter 3 mm, 25 mm square spacing, Driller, Freiburg, Germany). The reactor parts were mounted on aluminum construction profiles (Alváris, Suhl, Germany) and arranged in such a way that there was no contact between the reactor parts, i.e. the algae suspension fell freely from one part to the next. The retention tank was connected to the inlet module by a food safe PVC hose (Rauspiraflex Liquitec, Rehau, Rehau, Germany) via a magnetically coupled centrifugal pump (MKPG, Ventaix, Monschau, Germany) operated by a frequency inverter (Movitrac, SEW Eurodrive, Bruchsal, Germany). The volume flow rate of the algae suspension was measured using a magnetic-inductive sensor (MIK, Kobold, Hofheim, Germany) between pump and inlet module. Temperature and pH of the algae suspension were measured using a combination electrode (tecLine 201020/51-18-04-18-120, Jumo, Fulda, Germany) connected to a transmitter (ecoTrans pH 03, Jumo, Fulda, Germany). Evaporated water was automatically replaced with tap water added via a solenoid valve (Type 52, Gemü, Ingelfingen, Germany) when the level of the algae suspension in the retention tank fell below a level switch (LFFS, Baumer, Friedberg, Germany). CO_2 was added in the retention tank via a perforated hose (Solvocarb, Linde, Pullach, Germany) connected to a CO_2 mass flow rate controller (red-y smart, Voegtlin, Aesch, Switzerland). The frequency inverter, volume flow rate sensor, pH/temperature transmitter, level switch, solenoid valve, and CO_2 mass flow rate controller were connected to a data