Algal Research 10 (2015) 202–209

Contents lists available at ScienceDirect

Algal Research

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

Improving the photoconversion efficiency: An integrated photovoltaic-photobioreactor system for microalgal cultivation

Eleonora Sforza *, Elena Barbera, Alberto Bertucco

Department of Industrial Engineering DII, University of Padova, Via Marzolo 9, 35131 Padova, Italy

ARTICLE INFO

Article history:
Received 25 February 2015
Received in revised form 27 April 2015
Accepted 10 May 2015
Available online 23 May 2015

Keywords:
Scenedesmus obliquus
Continuous reactor
Light intensity
Photosynthetic efficiency

ABSTRACT

One of the main limitations to large-scale production of biofuels derived from microalge is the lower efficiency of sunlight conversion. The maximum theoretical value for photosynthetic efficiency is hardly achieved in real outdoor cultivation systems, mainly due to inefficient light utilization, in addition to photosaturation and photoinhibition phenomena that take place at high irradiances. This work is focused on testing different possibilities aimed at improving the overall photoconversion efficiency of microalgal production in photobioreactors. Two strategies were followed: the first one increases the portion of spectrum available for photosynthesis employing luminescent spectral-converter filters on the photobioreactor surface, the second one integrates microalgae reactors with photovoltaic panels, producing electrical energy together with biomass. Experiments were carried out both in batch and continuous laboratory scale flat-plate photobioreactors, at different light intensities and regimes, with two different species (*Nannochloropsis salina* and *Scenedesmus obliquus*), measuring the growth rate, pigment content, biomass concentration and photosynthetic efficiency. Results show that spectral-converters do not substantially improve the growth rate, while an integrated PV and PBR system could be a valid way to improve energy conversion performances.

1. Introduction

The growing demand for liquid fuels, which is expected to increase quite fast in the next decades, has driven research efforts into the development of numerous biofuel production technologies. Even though the oil price is recently dropped, due to the exploitation of shale oil and shale gas [1], this is a contingent occurrence which cannot face the long term demand for renewable energy sources to produce liquid fuels, and does not solve environmental issues. Among renewable sources, biofuels derived from the cultivation of microalgal biomass are worldwide recognized as a very promising sustainable alternative energy source that aims at replacing traditional fossil fuels [2]. Nonetheless, despite the many advantages that microalgae offer, compared to terrestrial crops, many factors still limit the feasibility of a competitive large-scale production facility, so that a sustainable algal biofuel industry is considered at least one or two decades away from maturity [3]. One of the main limits is the low photosynthetic efficiency (PE), which results also in a negative net energy balance of the process, together with the lack of a strong experience in the field, as a few pilot units are currently in operation. In this context, it is fundamental to gain a deeper knowledge of the energy balance of microalgal production in a photobioreactor (PBR), in order to better understand the energetic implications of industrial photosynthesis and to possibly optimize the efficiency of the cultivation process.

A key factor concerning autotrophic microalgal cultivation is played by light availability and utilization [4]. In fact, in view of an outdoor cultivation system, the main constraint to microalgae productivity is sunlight availability, which depends on location and other climatic factors [5]. It is evident that, in order to achieve massive algal productions, an autotrophic photobioreactor needs to have a large light-exposed surface. However, even if increasing surface results in a greater overall production, the energetic and economic costs can only be reduced by improving light use efficiency. For sunlight it has been estimated that the maximum theoretical efficiency of energy conversion (i.e., the fraction of light energy that is converted into biomass through photosynthesis) is about 11–12% [6]. Nonetheless, microalgae are in fact not able to absorb all the incoming energy and to convert all the harvested radiation into biomass, and actual photoconversion efficiency drops to values which are usually about 3% of the total light received [3].

Photosynthesis, in fact, depends on the absorption of light by pigments, the most important of which is chlorophyll-A (Chl-A), but several accessory pigments contribute to increase the spectral range absorbed as well. However, one of the main critical factors lowering the photosynthetic efficiency is the limited absorption of the incident sunlight: of the whole solar radiation spectrum, only about 43% is Photosynthetically Active Radiation (PAR, ranging from 400 to 700 nm) [7] that can be utilized by algae for photosynthesis. Moreover, only the blue and red wavelengths of the visible range (which constitutes the

* Corresponding author.
E-mail address: eleonora.sforza@unipd.it (E. Sforza).

http://dx.doi.org/10.1016/j.algal.2015.05.005
2211-9264/

PAR) are generally absorbed and utilized for photosynthesis, while the green and yellow wavelengths are reflected. To overcome this issue, luminescent PBR design for improved algal growth and photosynthetic pigment production through spectral conversion of light was recently proposed, where luminescent acrylic PBRs in blue, green, yellow, orange, and red colors capable of spectral conversion of light are used [8]. Solar spectral converters were also used as "luminescent backlight converter", placed at the bottom of PBR, as reported in Wondraczek et al. [9]. However, it is not clear yet if the exploitation of these filters may result in an overall increase of biomass productivity, in particular when light intensity is varying along with time as it occurs for sunlight.

In a second place, while a low irradiation is limiting, its excess leads to the formation of reactive oxygen species (ROS) that have an inhibitory effect on growth (the so-called photosaturation and photoinhibition phenomena). Therefore, when exposed to the high irradiances of sunlight, photosystems are not able to process the high flow rate of photons received. If photosynthesis is inefficient, the excess of light energy is dissipated as heat or as chlorophyll fluorescence to avoid damaging the photosynthetic apparatus, resulting again in an additional reduction of photoconversion efficiency. In the current literature, two strategies were proposed to limit the photo-damage: the first one involves the genetic modification of microalgae, which is currently under investigation [3]; the second one exploits the beneficial effect of high frequencies light–dark cycle, which can result in an improved energy conversion efficiency [10–12].

In this work two strategies are investigated to improve the light energy conversion in photobioreactors: i) increasing the portion of spectrum available for photosynthesis and ii) integrating microalgae photobioreactor (PBR) with a photovoltaic (PV) cell. In the first case, focus was given to the possibility of increasing light capture by employing a commercially available red spectral-converter filter on the PBR surface. Such a filter is able to absorb the green wavelengths and shift this radiation to the red range, potentially enhancing the total amount of photons that algae are able to utilize, which could result in increased productivity in the case of light-limited conditions. On the other hand, an integrated photovoltaic-photobioreactor (PV-PBR) approach is proposed, in which the front surface of a flat PBR is equipped with standard and low-cost photovoltaic cells. Such a configuration might increase the overall photoconversion efficiency of the whole cultivation system, by producing directly available electrical energy together with microalgal biomass. Moreover, if the PV cells are placed with a proper geometry, it could be beneficial to avoid or reduce photoinhibition phenomena.

Two microalgal species, *Nannochloropsis salina* (marine species) and *Scenedesmus obliquus* (freshwater species), were cultivated in both batch and continuous laboratory scale flat-panel PBRs, to test the performances of the solutions proposed in terms of biomass productivity and energy conversion efficiency.

2. Materials and methods

2.1. Algae strains and culture media

N. salina, strain no. 40.85 (obtained from SAG-Goettingen, Germany) was maintained and cultivated in f/2 medium, with 33 g L^{-1} sea salts (Sigma-Aldrich), buffered with 40 mM TRIS HCl pH 8, modified with a non-limiting nitrogen concentration (1.5 g L^{-1} $NaNO_3$). *S. obliquus* 276.7 (SAG) was cultivated in BG11 medium, buffered with 10 mM HEPES pH 8. For continuous experiments, BG11 and f/2 media were modified to guarantee non-limiting nutrient conditions (3 g L^{-1} $NaNO_3$ and 500 mg L^{-1} K_2HPO_4 in the case of BG11, 1.5 g L^{-1} $NaNO_3$ and 25 mg L^{-1} of $Na_2HPO_4 \cdot H_2O$ in f/2).

Pre-inoculum of both species was grown at 100–120 μmol of photons m^{-2} s^{-1}, provided by fluorescence lamps. The culture media and all the materials were sterilized in an autoclave at 121 °C for 20 min in order to prevent any contamination.

2.2. Experimental setup

The experiments were conducted both in batch and continuous mode, in flat-panel polycarbonate (PC) PBRs to maximize light utilization [13]. Reactors were exposed to different constant light intensities, ranging from 50 to 1000 μmol m^{-2} s^{-1} of PAR, and to alternated dark–light cycles to mimic outdoor irradiation conditions. Light was provided by a LED lamp (Photon System Instruments, SN-SL 3500-22, warm white color, with a spectral emission range from 400 to 780 nm). For day–night experiments, the LED lamp was set to reproduce the profile of PAR irradiation of a typical summer day in the location of Padova, Italy. The irradiation profile used is shown in Fig. 1. Irradiation data were taken from PVGIS Solar Irradiation Data (http://re.jrc.ec.europa.eu/pvgis/), and the month of July was selected as representative of the summer season, that corresponds to an integrated irradiation of 610 μmol m^{-2} s^{-1}, on 24 h basis. Photon flux density (PFD) at the reactor front surface and at the back was measured with a photoradiometer (HD 2101.1 from Delta OHM), which quantifies the PAR.

All experiments were carried out in a refrigerated incubator, and the temperature was kept constant at 23 ± 1 °C which is suitable for both the species investigated. Excess CO_2 (5% v/v mixed with air, regulated by two flowmeters) was supplied from a sparger placed at the bottom of the reactor, at a total gas flow-rate of 1 L h^{-1}. CO_2 bubbling also ensured culture mixing, which for *S. obliquus* runs was supplemented by the use of a stirring magnet. In batch experiments, *N. salina* was inoculated at an initial OD_{750} of 0.45, with a total reaction volume of 100 mL. The PBR had an irradiated surface of 125 cm^2 (10 × 12.5), and a thickness of 0.8 cm. *S. obliquus* was inoculated at initial OD_{750} of 0.5.

The correlation between cell concentration and OD was measured as:

$$\text{Cell conc} = 1 \times 10^7 \times \text{OD} - 1.5 \times 10^6. \quad (1)$$

The reaction volume in this case was equal to 150 mL, in a PBR with equal irradiated surface (125 cm^2) but wider depth (1.2 cm).

For experiments testing the efficiency of spectral conversion, a commercial product by PhotoFuel SAS (Paris, France) was used. The front PC plate was substituted with a red fluorescent polymethylmethacrylate (PMMA) plate modified with specially designed masterbatches and additives. The red spectral-converter was characterized in terms of absorption and emission spectra, using spectrophotometric and fluorimetric techniques (Cary Eclipse Varian spectrometer fluorometer).

PV-PBRs were realized applying flexible solar cells produced by PowerFilm onto the transparent PC front surface, with a measured PV photoconversion efficiency of about 5%; the PV panel (34 × 125 mm) was placed in the middle of the irradiated surface, so that through

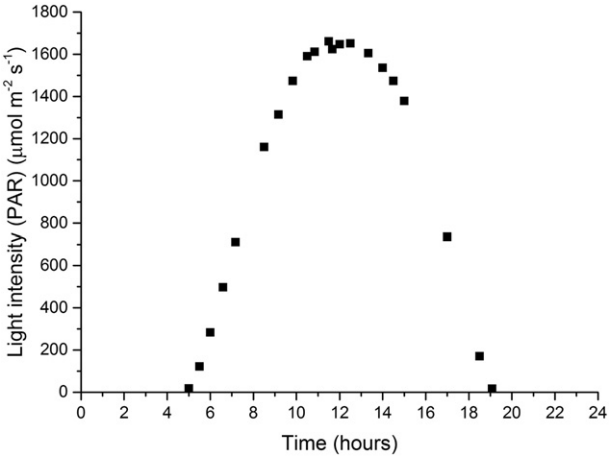

Fig. 1. Irradiation profile of the day–night experiments. Dots represent measurements of light intensity at the front surface of the PBR at different times of the day.