Renewable Energy 109 (2017) 13–21

Contents lists available at ScienceDirect

Renewable Energy

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

# Integration of dye-sensitized solar cells (DSC) on photobioreactors for improved photoconversion efficiency in microalgal cultivation

Elena Barbera [a,*], Eleonora Sforza [a], Andrea Guidobaldi [b], Aldo Di Carlo [b,c], Alberto Bertucco [a]

[a] Department of Industrial Engineering DII, University of Padova, Via Marzolo 9, 35131, Padova, Italy
[b] DYEPOWER, Via Aurora 9h, 00013, Fonte Nuova, Rome, Italy
[c] C.H.O.S.E.(Centre for Hybrid and Organic Solar Energy), Department of Electronic Engineering, University of Rome "Tor Vergata", Via del Politecnico 1, 00133, Rome, Italy

A R T I C L E I N F O

*Article history:*
Received 8 November 2016
Received in revised form
3 March 2017
Accepted 6 March 2017
Available online 7 March 2017

*Keywords:*
*Scenedesmus obliquus*
Continuous photobioreactor
Photovoltaics
Photoinhibition
Light spectrum
Dye solar cell

A B S T R A C T

Outdoor industrial-scale microalgae cultivation is limited by several factors, among which a low efficiency of overall light energy conversion plays a key role, mainly due to photosaturation and photoinhibition under high irradiations. This work aims at improving the overall photoconversion efficiency in a microalgal production photobioreactor (PBRs), by exploiting an advanced photovoltaic (PV) technology. A semi-transparent dye sensitized solar cells module (DSC) is placed on the irradiated surface, thus absorbing part of the incident light to produce electricity, while transmitted photons are used by algal cells for photosynthesis. Experiments are carried out in a continuous laboratory scale flat-panel PBR, at different constant light intensities and under a day-night irradiation regime, to ascertain the performances of this combined PV-PBR system in terms of biomass productivity and overall photoconversion efficiency, compared to traditional transparent PBRs. The results obtained show that the configuration proposed, combining biomass production with innovative photovoltaics technology, could be a valuable way to improve light energy utilization and efficiency in microalgal production.



## 1. Introduction

The growing demand for liquid fuels, together with the fact that current fossil fuels resources are a non-renewable, finite resource, has led research efforts towards the development of sustainable alternative energy sources, to replace some of our increasing energy needs. In this context, microalgae have been recognized as a very promising feedstock for bioenergy and biofuels production. These photosynthetic microorganisms are able to convert sunlight energy (which represents one of the main energy sources available on earth) into chemical energy stored as biomass, through the process of photosynthesis. In addition, compared to other photosynthetic organisms, such as terrestrial plants, they show higher growth rates and productivities, while at the same time not requiring arable or valuable land to grow [1–3].

Despite the many advantages offered by microalgae, industrial-scale production is still limited by several factors [1,2]. Among these, a low efficiency of light energy conversion plays a key role. The maximum theoretical value of photosynthetic efficiency (PE, i.e. the fraction of light energy converted into biomass through photosynthesis) has been estimated between 11% and 12% for solar energy [3]. This is mainly due to the absorption spectrum of photosynthetic organisms as well as to the energy requirements to convert sunlight into high energy molecules and to sustain the metabolism of the cells. Photosynthetic pigments (chlorophylls), in fact, absorb mainly the blue and red wavelengths of the Photosynthetically Active Radiation range (PAR, 400–700 nm), while the remaining wavelengths are poorly utilized.

In addition, to date, reported values of PE in real systems applications range between 2% and 7% [1]. The poor performances in terms of energy conversion efficiency are mainly linked to phenomena known as photosaturation and photoinhibition, which take place when algal cells are exposed to high light intensities. In fact, when the photon flux received by the photosystems is too high, they are not able to process all the photons absorbed, and the energy in excess is dissipated as heat or fluorescence to avoid the

* Corresponding author.
*E-mail address:* elena.barbera@studenti.unipd.it (E. Barbera).

http://dx.doi.org/10.1016/j.renene.2017.03.013
0960-1481/

formation of reactive oxygen species (ROS), which can induce an oxidative stress into cells [4].

As recently reviewed by Parlevliet and Moheimani [3], by combining different energy production systems, such as microalgal biomass production and photovoltaic (PV) technology, the solar spectrum could be totally exploited. This would allow both the production of biofuel and electricity from a single facility making efficient use of available land.

In a previous work, Sforza et al. [5] proposed an integrated photovoltaic-photobioreactor for microalgal cultivation, showing that covering a portion of the irradiated surface with silicon photovoltaic cells could help reduce photoinhibition under high light intensities, while allowing much higher photoconversion efficiencies. In fact, in addition to biomass production, part of the photons could be converted into electrical energy. The idea of combining photovoltaics with microalgal growth in order to better exploit incoming photons has received much attention in the last years, as also proposed by Bernard et al. [6], and a number of applications have recently been studied also by other authors. For instance, Parlevliet and Moheimani [3] proposed to apply a particular filter above the algal culture which transmits only certain wavebands, while the others are redirected to a solar cell for electricity production. Detweiler et al. [7] assessed microalgal growth under wavelength selective luminescent solar concentrator panels (LSC), applied to greenhouse roofs. The LR305 dye used in these LSC panels is able to absorb certain wavelengths and re-emit them as longer ones, part of which are guided within the panel and concentrated onto solar cells for electricity production, while the remaining are transmitted to the culture, reducing photoinhibition phenomena. However, in the available literature, only preliminary experimental results are available, and more efforts are required to ascertain the actual possibility to grow microalgae in such a combined system, from both an experimental and economical point of view.

In this paper, we propose a photobioreactor where a novel semi-transparent organic PV module is directly placed on to the irradiated surface: such a PV module absorbs a limited range of wavelengths, allowing to produce electricity, while the rest of the energy is transmitted through the PBR walls providing photons for microalgal cultivation. The aim of this work is to experimentally test the efficiency of this combined PV-PBR system in a continuous reactor, where the actual photosynthetic efficiency can be measured and the total energy produced is eventually evaluated. In addition, the effect of a partial PBR covering on the photoinhibition response under high irradiance and the effect on microalgal pigmentation are investigated.

## 2. Materials and methods

### 2.1. Algae strains and culture media

*Scenedesmus obliquus* 276.7 (SAG) was maintained in BG11 medium, buffered with 10 mM HEPES pH 8, in continuously stirred 250 mL sterile flasks, as a pre-inoculum. The culture was kept under a constant light intensity of about 100 μmol $m^{-2}$ $s^{-1}$. For continuous experiments, BG11 was modified in order to guarantee non-limiting nutrients concentrations (3 g $L^{-1}$ of $NaNO_3$ and 500 mg $L^{-1}$ of $K_2HPO_4$) [8], and focus on the effect of light only. To control the pH, the medium was buffered with 10 mM HEPES pH 8. Culture medium and all the materials were sterilized in an autoclave for 20 min at 121 °C, in order to prevent external contamination.

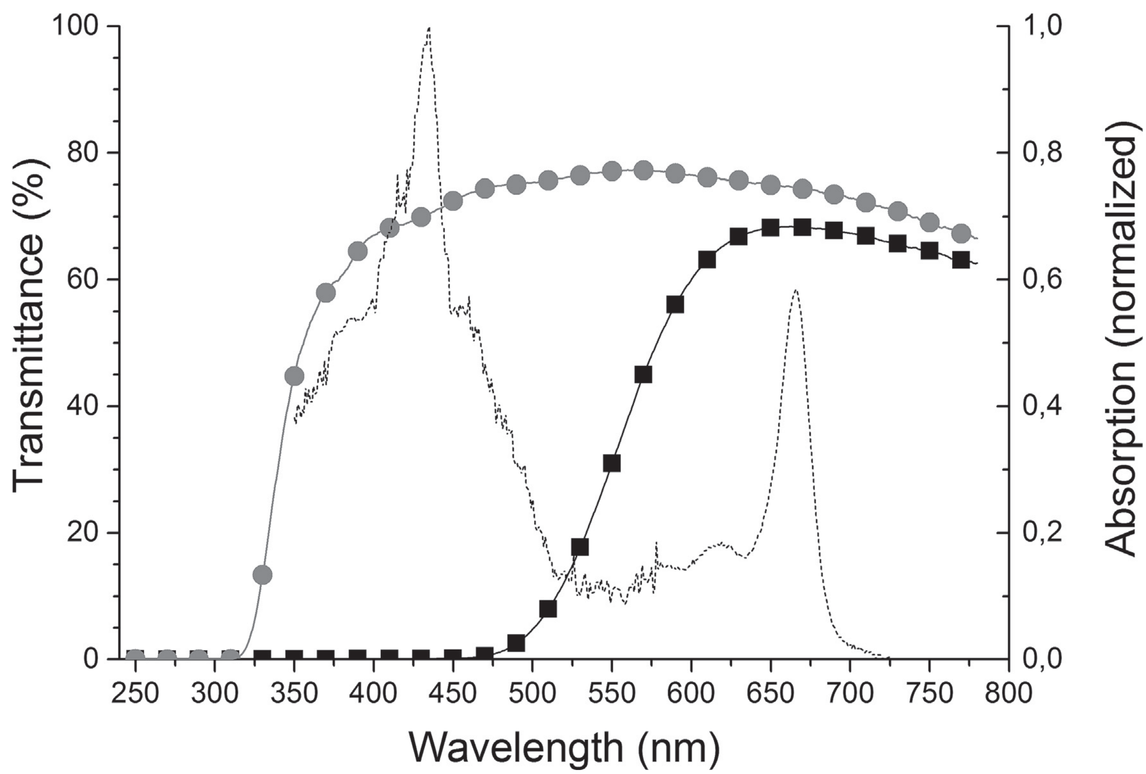


**Fig. 1.** Transmittance profiles of Dyepower DSC module, both of the active area (black, squares) and non-active area (grey, circles), performed via a spectrophotometer (Shimadzu UV-2700) in combination with a large sample compartment (Shimadzu MPC-2600). A typical absorption spectrum of extracted pigment from *S. obliquus* was shown as a reference (dashed line), which is normalized to the maximum absorption value.