How innovative light design can improve microalgae production

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***Abstract*— With this work we report on the design of two lighting systems based on LEDs to increase the efficiency and efficacy of microalgae production. Two lighting units are designed, discussed and their performances in biomass production of Arthrospira Maxima are evaluated. The first light design is used to demonstrate that an accurate spectral tuning can improve the photosynthetic efficiency as opposed to white light. The second light source has been designed to achieve high intensity, short pulses of light and demonstrate that under pulsing light regime the photosynthetic efficiency can be further improved. In particular we will focus into matching the absorption spectra of the algae light by accurately mixing the emission spectra of different Light Emitting Diode (LED) sources. By using pulsating light sources it also possible to boost the efficiency of the system by better exploiting the photon absorption and conversion principle.**

Keywords—LED, Algae, biomass, spectrum

I. INTRODUCTION

Microalgae are photosynthetic microorganisms including several taxonomic groups, with interesting perspectives in industrial applications. Due to their flexible and remarkable content of macromolecules of interest, they are of extreme importance to produce biomass that can be applied in the fields of renewable energy, agriculture and human health and nutrition. The fields of application include the following scenarios: i) in nutrition microalgae can provide supplements like: fatty acids, carotenoids, vitamins, minerals and food coloring [1], ii) as biofuels like bioethanol, they are a renewable and ecological sustainable alternative to liquid fossil fuels [2] but they can also be used as biomass in biogas production [3], iii) since microalgae can produce bioactive compounds they can be exploited for the production of treatment drugs like: antioxidants, antibiotics, antibodies, hormones, vaccines, and many more [1]–[4]. From an environmental point of view, microalgae might be crucial in the reduction of the carbon footprint, as they convert the CO_2 present in the atmosphere or exhaust gases into useful products such as carbohydrates, lipids, and other bioactive metabolites. The potential of microalgae is of extreme relevance, specifically into the current ecological transition phase, even though several technological and scientific limitations and challenges remain, one of the most relevant being the efficient use of light as a source of energy for the algae production. Microalgae are grown and produced in photobioreactors (PBR), where the biomass is cultivated in water suspension. A photobioreactor is a specifically designed tank where nutrients needed for algal growth are provided in the liquid medium, as well as the right amount of gases to ensure CO_2 supply and de-oxygenation. pH is another variable to be controlled, and mixing is required to facilitate mass exchange and guarantee uniformity and cell suspension throughout the volume of the tank. Temperature might be controlled by means of heat exchange unit in a closed feedback loop. In a PBR for industrial production algae are produced continuously, so a certain amount of suspension is continuously collected from the PBR to extract the biomass, while new (or recycled) water is added to keep the volume constant and provide nutrients supply. Being the primary source of energy for microalgae and sustaining the photochemical reaction which converts photons and nutrients in biomass, light is one of the most important variables to be controlled to obtain significant production. Even though sunlight can be exploited, its intrinsic variability strongly affects the stability of the culture and the overall photosynthetic efficiency [5]. Artificial light is a valid alternative, even though it makes the process more expensive in terms of energy requirements. The choice of light intensity and spectrum are critical for the efficiency as well as the setting of proper operating conditions in the PBR: a low light intensity might reduce the biomass productivity, while an excessive intensity might cause bleaching (photo-inhibition) and damage of the photosynthetic apparatus [6]. The spectrum instead can be crucial for the correct excitation of the algal pigments that can be also adapted to the impinging light color [7], thanks to acclimation phenomena. Light absorption also needs to be considered carefully in the thickness of the PBR, so that the energy is correctly reaching all the suspended culture. With this work we want to report on the development of specific light sources for photobioreactors applications, and how the accurate use of Solid State Lighting (SSL) can provide an important step into the manufacturing of higher efficiency PBRs.

II. SPECTRAL MATCHING AND EFFICIENCY OPTIMIZATION

A. Aim of spectral matching

The aim of spectral matching is the tuning of the light source spectrum in order to match the absorption spectrum of the target substance, so that energy present at wavelengths which are scarcely absorbed will not be wasted. In theory, the maximum energy transfer would be achieved by concentrating all the energy in the wavelength which is maximally absorbed by the target. On the other hand, in the case of microalgae, several pigments are present, increasing the spectral range of

absorption. Accordingly, a multiwavelength spectrum is required to achieve a good algal growth [8]. In our case the tuning will be carried out by means of mixing the emission spectrum of nearly monochromatic light source (LEDs) so that the resulting emission is localized at the wavelength of maximum absorbance.

B. Experimental details

The first step into spectral matching is the analysis of the absorption spectrum of the algal species which will be cultivated in the PBR. For this purpose, three different species were considered: Chlorella protothecoides, Arthrospira maxima and Tolypothrix tenuis, chosen as representative of green algae, cyanobacteria and cyanobacteria containing phycoerythrin, respectively. From Fig. 1, reporting the normalized absorption spectrum of the three species, it is possible to notice that they have a different absorption spectrum, but the main peaks are located in two spectral regions: blue peak at 440-460 nm and at deep red peak 650-700 nm; secondary peaks are present for C. protothecoides at 500 nm (cyan), for T. tenuis at 560 nm (green-yellow), and for T. tenuis and A. maxima at 630nm (red).

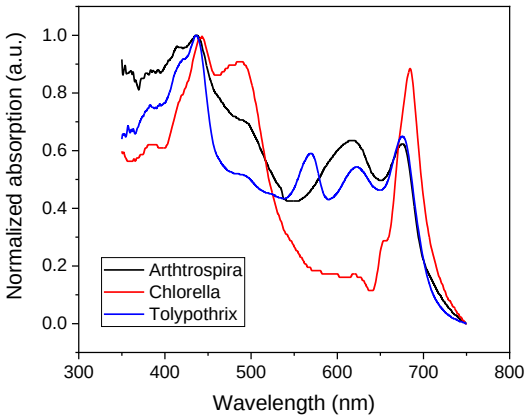

Fig. 1. Normalized absorption spectra of reference algae used for this work.

In this section we report on the development of a high efficiency lighting system which has been specifically designed to match the absorption spectrum of A. maxima . The selected emitters are high power single color LEDs, with a wavelength emission peak of 450 nm (blue), 630 nm (red) and 660 nm (deep red) respectively. Commercial off the shelf LEDs from several manufacturers and different models have been tested. We report in the following the results of the most efficient solutions together with a high efficacy (220 lumens per watt) 3600K white LED as a reference, the state of the art efficacy of the white LED is chosen to give a fair comparison. Their characteristics are reported in Table I.

TABLE I: LED SELECTION FOR ARTHROSPIRA SPECTRAL MATCHING AND EFFICIENCY OPTIMIZATION

Device type	**Peak wavelength**	**Chip size**	**Max. current**
High power blue LED	450 nm	2 mm^2	2 A
High power red LED	630 nm	1 mm^2	1 A
High power deep red LED	660 nm	2 mm^2	1.5 A
Mid power white LED	CCT:3600 K CRI:81	Non disclosed	0.2 A

The optical power emitted by these devices has been measured in a Labsphere LMS650 integrating sphere equipped with a Labsphere CDS610 spectrometer, the LEDs are biased by means of a Keithley 2614B source-meter unit. To avoid self-heating, measurements are pulsed at ambient temperature (25 ± 2 °C). The emitted optical power for the blue LEDs exceeds 2W at 1 A, and is the highest of the four devices as reported by the plot of Fig. 2A. In order to compare devices with different electrical characteristics, in Fig. 2 A the equivalent of 5 white LEDs in parallel has been plotted to compare with the other devices. For the specific purpose of this work, it is interesting to calculate the photon emission rate (photon flux) of the devices; it results from Fig. 2 B that both Blue and Deep Red LEDs are able to exceed an emission of 7 µmol/s at a current of 1 A. To design the continuous light unit (CLU) a total of 25 LEDs has been used in a 5 x 5 matrix, composed of 5 Blue, 10 Red and 10 Deep Red LEDs respectively. The resulting emission spectrum of the CLU, compared to the spectrum of the white LED, is reported in the Fig. 2 C, while on Fig. 2 D the plot of the efficiency as a function of current is reported. The decrease of the efficiency as current increases is typical for LEDs [8]. The light unit is then equipped with a multiple Total Internal Reflection lens to collimate the beam on the PBR front window. The structure used for the measurements is presented in Fig. *3*.

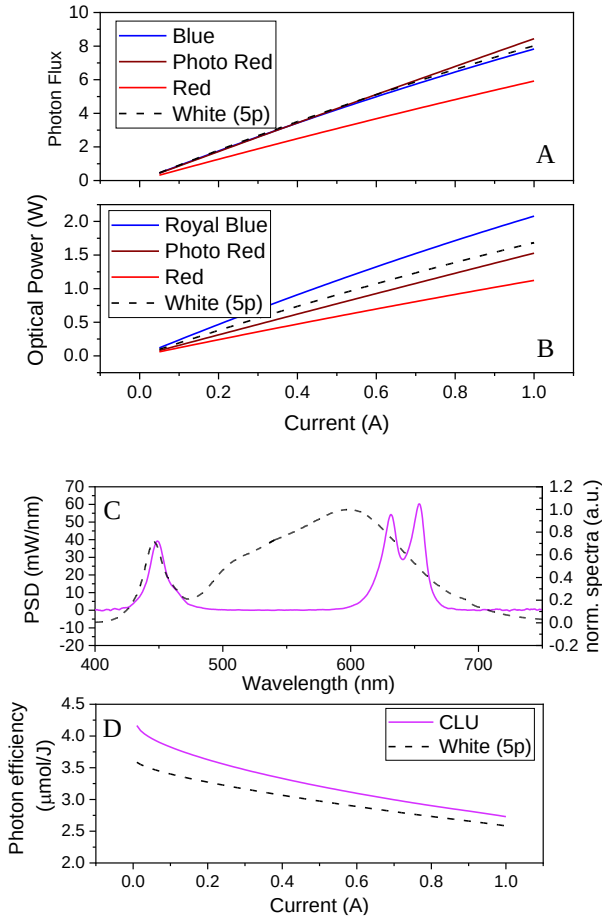

Fig. 2. Optical power and Photon emission rate of the selected LEDs (A and B), spectrum of the CLU compared to the white LED (C), and photon efficiency of the CLU and White LED (D).

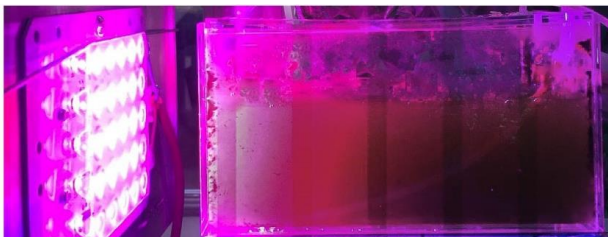

Fig. 3. Picture of the Continous Lighting Unit (left) and the PBR (right).

C. Results

In order to study the effects of light intensity on the efficiency of the production, the LED driving current of the CLU has been adjusted to achieve different photon flux density. To assess the performances of the designed CLU as compared to the white LED, cyanobacterium *A. maxima* has been cultivated at increasing light intensities under the different light sources. Growth kinetic parameters were retrieved from respirometry tests and used to calculate photosynthetic efficiency. Combining the CLU and white LED photon efficiency to the PBR photosynthetic production it has then been possible to compare the two global process efficiencies. Results are reported in Table II and demonstrate that a photosynthetic efficiency (ηPAR) of 33.42 ± 1.58 % [8] can be achieved with the CLU as compared to 16.07 % achieved by white light [9].

TABLE II: RESULTS OF THE TESTS CARRIED OUT ON DIFFERENT CONTINUOUS LIGHT SOURCES

PFD	**PBR depth**	**Residence time**	**LED**	**ηPAR**	**ηtot**	**Ref**
µmol/m²/s	*cm*	*days*		*%*	*%*	
200	3.5	1.6	White	13.92 ± 1.50	9.05 ± 0.97	[10]
400	3.5	1.6	White	11.99 ± 0.54	7.74 ± 0.35	[10]
400	3.5	1.0	White	16.07 ± 1.37	10.44 ± 0.89	[10]
60	14.5	1.33	R/B	33.42 ± 1.58	26.40 ± 1.20	[8]
150	14.5	1.33	R/B	24.23 ± 0.68	19.00 ± 0.50	[8]
300	14.5	1.33	R/B	14.43 ± 0.33	11.20 ± 0.20	[8]
300 (opt.)	14.5	0.88	R/B	17.07 ± 0.32	13.20 ± 0.20	[8]

III. DESIGN OF PULSED LED LIGHT SOURCE TO IMPROVE

A. Aim of pulsed light design

The use of pulsed light in a PBR can potentially increase the energy efficiency of the produced biomass. The advantage of using high intensity short pulses is based on two separate concepts: 1) inside the PBR the light intensity decreases quickly as the depth increases due to microalgae absorption: with high intensity pulses it is possible to improve the light penetration, without inducing photobleaching on the algae; 2) the photons captured by the algae pigments require a certain time to be converted into energy due to the kinetics of the linear electron transfer chain, and during this time no other photons can be absorbed: a short light pulse followed by a dark period can therefore result in a higher efficiency since photons are not wasted during the algae photon-energy conversion process.

When operating in pulsating mode, the light source is required to achieve the same average Photon Flux Density of the light source operating in continuous mode in order to achieve comparable results in terms of algal productivity. Operating in short pulses with low duty cycle requires a much higher peak emission, although a duty cycle of approximately 2% can be achieved simply by increasing the driving current of the CLU. A specific pulsed lighting unit (PLU) has been designed in order to achieve a higher peak light intensity.

B. Design of the light source

PLU is equipped with 4 times the number of LEDs of the CLU (100 in total), and a specific reflective optical mixing chamber has been designed in order to allow a better optical coupling with the PBR. LEDs are also driven at a much higher current (up to 1A) for short pulses. The designed PLU is a 10 x 10 LED matrix subdivided into 10 series of 10 LEDs each. Each series is composed of 2 blue LEDs, 4 red LEDs and 4 deep red LEDs, the current of each series is regulated at a maximum value which can be set up to 1A by a specifically designed current controller circuit (CCC). As presented in Fig. 4, the CCC senses the voltage drop on a shunt resistor and by means of a negative feedback regulates the gate voltage of a MOSFET so that the current is kept constant. The current value can be set by adjusting the value of the sense resistor. The integrated circuit is equipped with a Pulse Width Modulation (PWM) input which, when logically high, enables the output, and is then used to control the current waveform and generate the square light pulses. The PWM inputs of the 10 CCC are connected to a single signal generated by an ISO-TECH AFG-2225 waveform modulator operating in pulse mode.

C. Results

A first set of experiments has been carried out by using the CLU in a pulsed regime with a single CCC driving the 25 LEDs connected in series, a second set of experiments at higher intensity has been carried out by means of the PLU, the shape of the pulses for 10 µs and 100 µs are reported in Fig. 5, while the complete set of experimental conditions are reported in Table III.

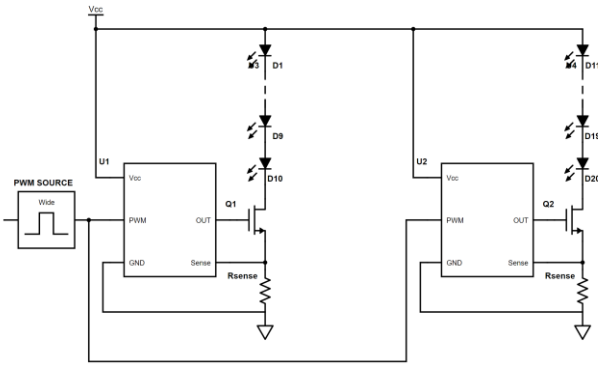

Fig. 4. Sketch of the electronic control circuit of the PLU, 2 of the 10 circuits are shown.

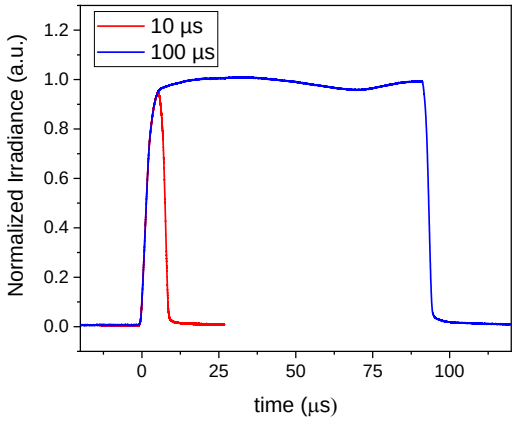

Fig. 5. Normalized Waveform of the light pulses emitted by PLU for light periods of 10 µs (red line) and 100 µs (blue line).

TABLE III: RESULTS OF THE TESTS CARRIED OUT ON DIFFERENT CONFIGURATIONS OF CLU AND PLU

LU	Avg. PFD µmol/m²/s	Peak PFD µmol/m²/s	Light period µs	Freq. Hz	Duty Cycle %	Mult. factor	Ref.
CLU	300	8108	10	3700	3.7	27.0	
		11600	100	275	2.75	38.6	
		10800	200	139	2.78	36	
		16216	500	37	1.85	54.1	
		12500	1000	24	2.4	41.7	
PLU	300	11600	100	275	2.75	38.7	[11]
		17850	10	1680	1.68	59.5	This work
		17850	100	168	1.68	59.5	[11]
		35700	10	840	0.84	119	This work
		35700	100	84	0.84	119	[11]

It is noteworthy that in some of the conditions, as reported in Figure 6, pulsed light allowed to obtain a higher biomass concentration at steady state compared to that obtained under continuous irradiation. However, the duration of the pulse, as well as its intensity have an effect on growth. In particular at a peak intensity of 35000 µmol/m²/s photons the microalgal biomass appears to be photo-inhibited.

IV. CONCLUSIONS

Two different light sources specifically engineered to improve the efficiency of microalgae growth were designed, built and operated. The first light source is designed to optimize the absorption matching of Arthrospira maxima, high efficiency blue, red, and photo-red LEDs have been adopted with an electrical to optical efficiency of 80 % at low currents (70 mA). By lighting a Photo bio reactor at a photon flux density of 300 µmol/m²/s an overall efficiency of 13.2 % was achieved as opposed to an efficiency of 10.44 % for a white LED in comparable conditions. The second light source is designed to operate in pulsing mode and achieve an extremely high emission intensity for a short pulse duration. Results indicate that by using pulsing light it is possible to exploit both physical and biological mechanisms which more than doubles the efficiency of the continuous light with the same spectrum. The maximum efficacy is operated with a pulse time of 100 µs and a frequency of 168 Hz, corresponding to a peak intensity ~ 60 times higher with respect to the average value. In conclusion, with this work, we demonstrate the advantages of using a spectral matching technique and a pulsing light technique to improve biomass concentration, and microalgae cultivation efficiency.

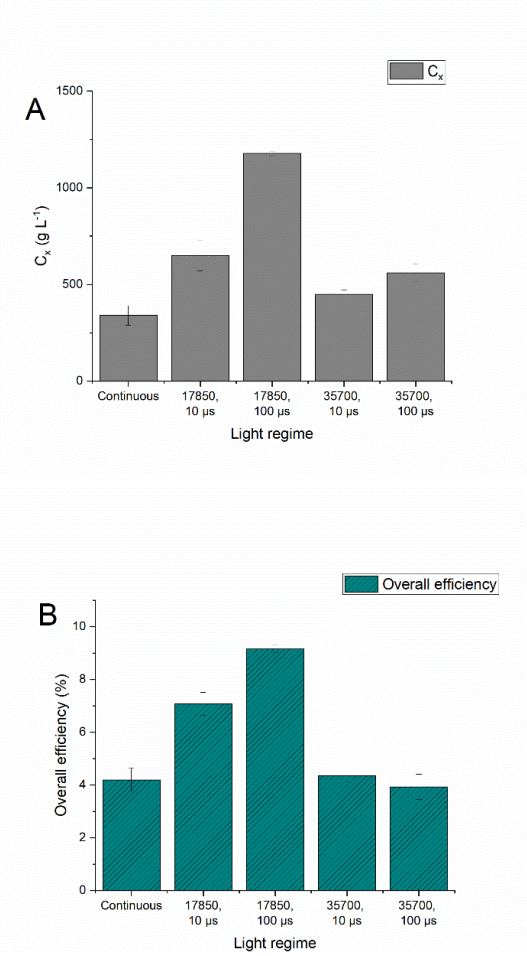

Fig. 1. Biomass concentration at steady state (A) and overall efficiency (B) under continuous light and pulses with different intensity and light period.

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