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Application note

Application note: A novel low-cost open-source LED system for microalgae cultivation

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ABSTRACT

This application note introduces an Arduino-based LED system useful for cultivation of various microalgae species as well as other plants. The system is based on RGB (APA102C) LEDs connected to an external Arduino microcontroller allowing flexibility via programming, modification, and upgrades. We describe in detail the C functions that produce white light and mixed colors in LED strips as well as the ability to generate intermittent/flashing/pulsing light. The capabilities of the system offer unique applications in industry and research. Our aim is to provide a low-cost and open-source tool in order to improve and promote cultivation of photoautotroph species (bacteria, microalgae or plants) using LEDs.

1. Introduction

The impacts of global warming, increasing prices of commodities, diminution of natural resource and population growth have intensified the research on finding future crops. Microalgae is a promising alternative crop due to their capability to perform photosynthesis, rapid growth, increase yield potential, stress resistance, production of bioactive components and usage as feedstock. Phototrophic cultivation of microalgal cells is carried out in laboratories in an environment of stable and calibrated illumination in clear flasks, culture vessels, bottles, tanks, or alternatively outdoor in order to take advantage of solar energy using tubular or cylindrical photobioreactors, or in open ponds/raceways (Bajpai et al., 2014). Nevertheless, despite considerable research and effort done in the past decades major issues concerning microalgal cultivation systems exist and improving the systems in use are needed. Furthermore, microalga-based applications that have reached industrial scale are relatively scarce, mainly due to high production costs involved, given the current market prices of the products of interest (Carvalho et al., 2011).

The usage of closed bioreactors as an artificial growing system is now established and like some other growing systems a requirement to ensure microalgae growth, the addition of light sources is needed. Light and difficulties associated with its control are a major factor in microalgal cultivation and the bottleneck caused by using conventional light sources can now be addressed by employing innovative technologies such as Light Emitting Diodes (LEDs) (Carvalho et al., 2011; Yam and Hassan, 2005).

The objective of this application note is to develop and promote a low-cost, open-source light solution for microalgae cultivation based on LEDs and the Arduino microcontroller. This note also provides concise background on LEDs, Arduino and photosynthesis as well as the hardware designs and source codes needed. The core topics discussed briefly in the background are LEDs and Arduino microcontrollers (Section 2.1), photosynthesis (Section 2.2) and benefits and disadvantages of LED systems (Section 2.3).

Both the hardware and source codes can be easily modified or scaled up in order to be used in various microalgae cultivation setups and biotechnology research, but can also be applied to other experiments involving plants/non-plant setups which require changeable light regimes. The hardware and source codes section including the LEDs system and an optional cooling solution (fan based) are described in Section 3.1. The source codes include in this paper (different colors, mixing different colors and flashing light) are shown in Section 3.2.

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2. Background

2.1. Light, LEDs and Arduino microcontroller

Visible light is one segment of the electromagnetic radiation spectrum which can be treated as a wave but also as a particle, which is called a photon. Light with a wavelength between 380 and 750 nm has the energy content to sufficiently produce chemical changes in the absorbing molecules while light sources with a wavelength higher than 750 nm have an energy content that is too low to mediate chemical change and the energy absorbed in this range can only be converted to heat. Further, wavelength radiation below 380 nm gives rise to ionizing radiation such as X-rays, which have such a high energy content that it ionizes the molecules it encounters (Kommareddy and Anderson, 2004) and therefore can be quite damaging to living biological systems. The biomaterials that adsorb certain light wavelengths are called pigments and some are essential for photosynthesis. Chlorophylls, carotenoids (carotenes and xanthophylls) and phycobilins are three major classes of photosynthetic pigments in microalgae (Begum et al., 2015). The selection criteria of artificial light sources include high electrical efficiency, low heat dissipation, good reliability, high durability, reasonable compactness, low cost and spectral output falling within the absorption spectrum of the microorganism of interest (Bertling et al., 2006).

Cultivation of microalgae (indoors) require artificial light as it provides better regulation of the photosynthetic photon flux density, photoperiod, and light spectra. Among artificial light sources LEDs are an excellent light source and have gained popularity and flourished for the past few years due to their properties (high efficiency, reliability and low power consumption), decreasing prices and the ability to deliver a low-cost light solution. Conventional light sources (e.g., mercury, metal halide and halogen lamps) are known to be accompanied by large energy losses, which are attributed to high thermal irradiance and often require various auxiliary devices in specific experimental settings such as a set of filters for spectral tuning and shutters to control exposure duration (Teikari et al., 2012).

The recent development of high brightness and addressable (programmable) Red, Green, Blue (RGB) LEDs, driven by a microcontroller have increased their usage in commercial applications. The mix of three single primary colors RGB LEDs is a technique used to generate white light and offers an excellent white light color rendering. By changing the relative intensity of the different color LEDs, it is relatively easy to change the hue of this light source for different applications and with no quantum deficit arising from the Stokes shift loss. However, a relatively complicated external detector and feedback system are required to control the intensity of the light. Furthermore, each LED will degrade at a different rate over a period of time, therefore, certain light intensity ratios emitted by each of these LEDs must be maintained (Yam and Hassan, 2005).

Arduino is an open-source electronics platform based on easy-to-use hardware and software launched in 2005. Arduino platforms are the most well-known and fast spreading electronic prototype developed with the aim to create control devices for projects that are easy to use and inexpensive to acquire. The Arduino Uno is a microcontroller board based on the ATmega328P with 14 digital input/output pins (of which 6 can be used as Pulse Width Modulation (PWM) outputs), 6 analog inputs, 16 MHz quartz crystal, USB connection, power jack, In-Circuit Serial Programming (ICSP) header and a reset button (Arduino—HomePage).

Despite the availability of off-the-shelf microcontrollers and LEDs, their widespread usage in scientific research is limited. There are few scientific articles, technical notes and applications dedicated for the usage of LEDs for plant cultivation and experiments (Shimada and Taniguchi, 2011; Janda et al., 2015; Yeh and Chung, 2009).

2.2. Photosynthesis

Photosynthesis is a photobiochemical process using light energy to produce ATP and NADPH, ultimately consumed in the conversion of CO_2 to organic molecules. Light is a crucial element both in quantity and quality and has to be efficiently transported to the microalgae vicinity to allow photosynthesis. Light is a major factor but, if present in excess, may lead to the formation of harmful reactive oxygen species (ROS) and oxidative stress, phenomena that limit primary productivity. The amount of light energy can influence photosynthesis rates in a number of ways like, availability of the photosynthetic active radiation (PAR), wavelengths, frequency of Light:Dark (L:D) fluctuations, L:D ratio, light acclimated state of the microalgae and the light "history" (continuous or pulsed) (Grobbelaar, 2010).

The first steps of light capture by plants are close to maximum efficiency while later steps are less efficient. It is common to say that the solar energy to biomass conversion will eventually be 1–8% while microalgae seem to absorb light more efficiently, with a photosynthetic efficiency of ca. 20% (Carvalho et al., 2011). Photosynthesis is divided into two parts, light-dependent reactions and light-independent reactions (dark reactions/Calvin cycle) which are considered as the ultimate rate-limiting processes in photosynthesis. It is assumed that dark periods during microalgae growth are necessary but on the other hand, long dark periods (e.g., several hours) will cause microalgae to switch to respiration processes which might lead to a lower growth rate and biomass loss.

As mentioned above light is necessary, and excessive or insufficient light constrains growth and metabolite yields. The photonic flux for photosynthesis (photosynthesis-irradiance curve) can be divided into three categories: (1) light-limited region where the photosynthetic efficiency increases with a rise in irradiance; (2) light saturation area in which the photosynthetic processing capacity of the culture is at maximum and the excessive photonic flux scatters as heat or fluorescence; and (3) photo-inhibition region where increase in light intensity becomes hazardous to the culture which causes a decreased growth rate at the end of the cycle. In photo-inhibition, the photosystem II can be rapidly damaged leading to a decrease in bioproductivity while the photonic flux increases. Microalgae undergo photo-oxidation when the chlorophyll molecule is excited due to high photonic flux, this unstable form can react with oxygen creating an excited oxygen (free radical state). The excited oxygen can cause several unwanted processes, one of which is a reaction with fatty acids which can be harmful to cell and organelle membranes (Carvalho et al., 2011).

Light quality is known to affect microalgal growth as the number of photons in the blue or red wavelengths that can be captured by a chlorophyll molecule depends on the microalgae cellular architecture, pigment composition, and chloroplast arrangement. In microalgal cultures, it has been suggested that at least 5–10% of photons of blue light are required (if red light were used) for other metabolic functions besides photosynthesis; hence, a small amount of white light may be needed in photobioreactors (PBRs), in order to account for such non-photosynthetic needs (Kommareddy and Anderson, 2004). The blue and red wavelengths and their ratio can also affect the biochemical composition, several metabolic pathways and gene expression (Schulze et al., 2014).

A continuous light supply is often used for microalgal cultivation while intermittent/flashing/pulsing light has been investigated to a limited degree due to technical issues; although it is a theoretically suitable alternative and the first experiment using flashing light was done with *Chlorella* by Emerson and Arnold in 1932. From previous works the following facts can be deduced: