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Evaluation of wavelength selective photovoltaic panels on microalgae growth and photosynthetic efficiency

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ABSTRACT

Large-scale cultivation of microalgal biomass in open systems can benefit from the low cost of using natural sunlight, as opposed to artificial light, but may encounter problems with photoinhibition, high evaporation rates, potential contamination and high energy demand. Wavelength selective luminescent solar concentrator (LSC) panels can solve some of these problems when incorporated into low-cost sheltered structures for algal biomass production that concurrently produce their own electricity by harnessing select portions of solar energy, not used for algal growth. The LSC panels in this study contained a fluorescent dye, Lumogen Red 305, which transmits blue and red wavelengths used for photosynthesis with high efficiency, while absorbing the green wavelengths and re-emitting them as red wavelengths. The fluorescently generated red wavelengths are either transmitted to boost algal growth, or waveguided and captured by photovoltaic cells to be converted into electricity. We found that different strains of microalgae (currently used commercially) grew equally well under the altered spectral conditions created by the luminescent panels, compared to growth under the full solar spectrum. Thus this technology presents a new approach wherein algae can be grown under protected, controlled conditions, while the cost of operations is offset by the structure's internal electrical production, without any loss to algal growth rate or achievable biomass density.

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1. Introduction

The harvest of metabolic compounds from microalgae for the production of nutraceuticals, bioplastics, biofuels, cosmetics, animal feed, and other natural products has become of increasing interest in recent years, particularly as some of these replace petroleum based products [1–3]. Although technological and biological optimization of microalgal biomass production is constantly evolving, growing large quantities of algae in open and closed cultivation systems in an economically viable and sustainable manner is still a challenge. The electrical requirement through all steps from cultivation, harvesting, and product extraction is a major sink of resources [4,5]. One way to supplement energy needs is the production of electricity within the plant *via* anaerobic digestion of less valuable biomass [6]. A more direct approach is the use of luminescent solar concentrator (LSC) panels, which can absorb solar radiation and convert light of specific wavelengths into electricity *via* photovoltaic cells [7].

Luminescent solar concentrators were first developed in the 1970s, but have gained renewed interest in recent years with the improved stability and resistance of organic dyes [7–10]. A transparent panel is infused or coated with luminescent organic dyes or quantum dots (semiconductor nanocrystals). Light is collected by fluorescent particles distributed over a large surface area and is re-emitted as longer wavelengths, which are then guided within the panel by total internal reflection and are concentrated onto solar cells, usually located on the edge of the panels [7,8].

The LSC panels used in this study, described in Corrado et al. [10], were infused or coated with a fluorescent organic dye, Lumogen Red 305 (LR305), which absorbs wavelengths shorter than 400 nm and green wavelengths between 500–600 nm, re-emitting the latter as longer wavelengths in the 600–750 nm range. About 80% of the red light is trapped and waveguided in the panels, a significant portion of which is captured by front-facing photovoltaic (PV) cells and converted to electricity, while half of the remaining 20% of light causes enhanced red light illumination beneath the panels (see Fig. 1 in Corrado et al. [10]).

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The transmission of the LSC panels is dependent on the concentration of the dye used.

LSC panels can easily be installed on existing greenhouse structures to provide an enclosed space with reduced evaporation rates, and reduced photoinhibition due to the selective spectrum, while also producing energy for greenhouse operations using the green photons which are of lower value to photosynthetic organisms [11]. Currently, these panels can produce ~50 W/m^2 on a sunny day (they will also produce energy on a cloudy day by efficiently capturing diffuse light) and, dependent on the scale of production, can cost as little as $100/m^2 one-time cost for panels with a twenty-year or more lifetime (personal communication C. Corrado).

The maximum transmission of the LR305 panels in the blue and red wavelength bands correlates well with the maximum absorbance of photosynthetic pigments. The absorbed green light, which is re-emitted as longer wavelengths, provides an additional source of red light, making these panels ideal for cultivating microalgae, cyanobacteria and plants. Photosynthetic organisms are generally green because they reflect light with wavelengths in the green region of the visible solar spectrum. Algae have photosynthetic pigments (chlorophyll *a*, *b*, *c*, and *d*) that absorb light in the blue (~420–480 nm) and red (~620–680 nm) regions of the photosynthetic active radiation (PAR) spectral range (400–700 nm) [12]. Other accessory photosynthetic and photoprotective pigments, such as carotenoids absorb light between 420–500 nm. Aside from chlorophyll *a* (chl *a*), cyanobacteria also have light-harvesting antennae called phycobilisomes containing pigments (*e.g.*, phycocyanin and phycoerythrin) that absorb green, yellow and orange light (~490–650 nm) [12,13].

Any technology that results in changes to the light field experienced by photosynthetic organisms (such as greenhouse panels), particularly ones being raised for commercial products, needs to take into account the effect of the spectrum of available light on growth and product formation rates. The importance of light quality for algae growth and cell composition has been investigated using light-emitting diodes (LEDs) in short-term experiments and at low irradiance levels in laboratory settings. Studies by Lee and Palsson [14], Matthijs et al. [15], and Gordon and Polle [16] suggested that monochromatic red light enhances algal growth rates compared to white light. Fu et al. [17] found that *Dunaliella salina* had higher biomass production and carotenoid (β-carotene and lutein) accumulation at a higher irradiance (170 μE m^{-2} s^{-1}) when 75% red and 25% blue light were combined, compared to red light alone. Katsuda et al. [18] observed that *Haematococcus pluvialis* showed increased concentrations of astaxanthin, at a cost of cell growth suppression under purple-blue light (380–470 nm), compared to red, green, blue, purple and fluorescent light at extremely low light intensities (2–12 μE m^{-2} s^{-1}). Das et al. [19] grew *Nannochloropsis* sp. over a period of 8 days, under white, green, red and blue light, and found that growth rates were higher under blue light alone.

Overall, these light quality studies and many others demonstrate that at least red and/or blue light are essential for the growth of algae. These observations were the impetus to study the growth of algae using solar radiation filtered through LSC panels that transmit blue and red wavelength bands, while retaining most of the green wavelengths for electricity production. Thus, the objective of this study was to compare growth rates, photosynthetic efficiency and pigment production in various green algae and cyanobacteria grown under spectrally selective LSC panels containing the dye LR305 and a clear, standard type greenhouse.

2. Materials and methods

2.1. Algae strains

Four strains of microalgae (*Chlorella vulgaris*, *D. salina*, *Chlamydomonas reinhardtii*, *Botryococcus sudeticus)* and a cyanobacterium (*Spirulina platensis*) (see Table 1 for strain information), were chosen for this study due to commercial interest in their pigments, proteins, lipids and/or other nutritional values [1,2,20]. The cultures were grown in media shown in Table 1 using aseptic techniques to minimize contamination.

2.2. Growth experiments

2.2.1. Small batch cultures of algae grown under LSC panels with different LR305 dye concentrations

Algae cultures were started indoors in 2 L Erlenmeyer flasks placed on a gyratory shaker (New Brunswick Scientific — model G10, New Brunswick, NJ) under "cool-white" light (Phillips — model F32T8/TL741, Alto, Somerset, NJ — color temperature 4100 K). Cultures were then gradually adapted to ambient near full solar light in a greenhouse, using increment reduction in neutral density screening, over a period of 2–3 days prior to performing growth experiments at NASA Ames Research Center (ARC), Moffett Field, CA (37°25′38″N, 122°3′43″W).

The acclimated cultures were transferred into fresh media (see Table 1 for respective medium for each strain) to a final optical density at 750 nm (OD_{750}) of 0.1. One hundred mL aliquots of the diluted culture were transferred to twelve 250 mL Erlenmeyer flasks. Triplicate flasks were placed in four different acrylic aquaria filled with water for temperature control. Submersed aluminum tubes with circulating water from an aquarium chiller (AquaEuroUSA — model MC ½ HP, Gardena, CA) reduced water temperature fluctuations in the aquaria. Water temperature in each aquarium was measured every 10 min using temperature loggers (Onset Hobo Water Temp Pro v2 — model U22-001, Bourne, MA). Water temperature varied between 15.8 °C and 23.8 °C, with an average of 18.5 °C.

Irradiance was measured as PAR using a LI-COR quantum sensor (model LI-190SA) coupled with a LI-1400 data logger (LI-COR, Lincoln, NE). The NASA ARC greenhouse was covered with Acrylite OP-4 sheets (Cyro Industries, Parsippany, NJ) which allows for 80% light transmission around 300 nm, and ~92% transmission >400 nm of the solar UV to pass through. Irradiance measurements inside the greenhouse, adjacent to the LSC panels, reached 1090 μE m^{-2} s^{-1} in the winter, with an average day/night irradiance of 201 μE m^{-2} s^{-1}. During the summer, irradiance measurements reached 1529 μE m^{-2} s^{-1}, with an average day/night irradiance of 382 μE m^{-2} s^{-1}.

Flasks were topped with rubber stoppers and bubbled with air filtered through a 0.2 μm syringe filter (Fisher Scientific part #194-2520, Waltham, MA) to provide adequate airflow in the flasks and to maintain the algae in suspension. Three of the aquaria containing flasks of algae were covered with LSC panels containing different concentrations of the dye LR305; these were designated LSC light, LSC medium and LSC dark hereafter. The fourth aquarium was covered with a clear acrylic panel and served as the control (Fig. 1A).

2.2.2. Spectra transmitted through LSC and clear panels

The spectral composition of light transmitted through the LSC panels and the clear panel was measured (between 350–800 nm) with a spectrometer (Ocean Optics — model USB4000-VIS-NIR, Dunedin, FL) and normalized to the solar spectrum (Fig. 2). There was decreasing transmittance of purple and blue (~400–495 nm) and green (~495–570 nm) light with increasing dye concentration. The amount of transmitted red light with wavelengths between 600 and 730 nm was similar for all three dye concentrations, and exceeded the red light transmittance of the control panels above 630 nm. The transmittance (PAR) of the clear panel, and LSC light, medium and dark panels at peak irradiance were 98%, 77%, 66% and 60%, respectively, in relation to full solar irradiance.

2.2.3. Fifty-liter raceway cultures of D. salina grown in an LSC and a clear greenhouse

To investigate the effect of LSC light filtration on the growth rates of large scale cultures, the green alga *D. salina* was grown in 50 L raceways in a greenhouse with LSC medium panels as well as in a separate greenhouse with clear panels (also referred to as control) (Fig. 1B) at the