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Use of wavelength-selective optical light filters for enhanced microalgal growth in different algal cultivation systems

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HIGHLIGHTS

- Nano-material light filters were used to filter certain spectrum of wavelengths.
- The light filters improved algal yield for 13–34% in flat panel photobioreactors.
- The light filters improved algal productivity for 70–100% in attached growth system.
- The light filters show a great potential to be used in large-scale algal production.

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ABSTRACT

This work is to use thin film nano-materials as light filters to selectively transmit certain wavelengths from natural sunlight to algal culture. A red light filter (620–710 nm) and blue filter (450–495 nm) were evaluated. Algae were grown in flasks, flat panel reactors, and rotating algal biofilm (RAB) system. It was found that the light filters did not improve algal growth in flask cultures, probably due to the additional reflection of light by the glass wall of the flasks. However, the light filters significantly ($P < 0.05$) improved biomass yield (13–34%) in flat panel reactors and biomass productivity (70–100%) in RAB system, depending on the growth mode and lighter filters. Such improvements may be due to the eliminating the ultra-violet (UV) damaging the cellular structure. The biomass compositions did not change significantly among different light-filter cultures ($P > 0.05$). The research shows a great potential of using light filters to improve microalgal growth.

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1. Introduction

Microalgae represent a group of photosynthetic organisms that are capable of growing rapidly while only requiring light and basic nutrients. As a promising biomass feedstock, microalgae can be used for producing a variety of bio-based fuels, feeds, and chemicals. The most fuel commonly produced from microalgae is biodiesel produced from transesterification of algal lipid. This is due to microalgae having appropriate percentages of fatty acids that can be readily converted into biodiesel through a high-tech bio-refinery process (Likozar and Levec, 2014; Sostaric et al., 2012). Other types of algal derived biofuels include alcohol (Wang et al., 2011), biogas (Gunaseelan, 1997), and bio-oil (Yang et al., 2004). In addition to various types of fuels, algal biomass can also be used for producing fertilizers (Mulbry et al., 2008), aquacultural feeds (Duerr et al., 1998; Hemaiswarya et al., 2010), and nutraceuticals (Hudek et al., 2014). For example, one of the most common value-added chemicals includes the fatty acid docosahexaenoic acid (DHA). This fatty acid is commonly consumed by pregnant women and newborn children to enhance brain and retinal functions (Uauy et al., 2003).

In the mass production of microalgae, in either open ponds or closed photobioreactors, light limitation is a major factor restricting cell growth. Due to the mutual shading caused by algal cells, light penetration is reduced exponentially with depth (Lee, 1999). The poor light penetration often results in an ultra-low cell density. For example, algal cell density in open ponds can be as little as 0.5 g/L, and 2–6 g/L in photobioreactors (National Algal Biofuels Technology Roadmap, 2010).

In addition to light intensity, the wavelength of the light source also plays an important role in the algal culture (Wahidin et al., 2013). While a small number of algae can perform heterotrophic growth, the majority of algal growth is phototrophic, which must rely on solar radiation to perform photosynthesis (Clarens et al.,

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2010). However, natural sunlight is not optimized for algal cell growth due to the wide light spectra including ultra-violet (UV) and infrared red (IR) rays which can damage the cellular structure (Holzinger and Lutz, 2005). This damage is particularly severe when light intensity is strong (PAR > 750 μmol s^{-1} m^{-2}) which is often encountered in a sunny day in an outdoor open pond or photobioreactor where the light intensity can reach to 2000 μmol s^{-1} m^{-2}; although, in some specific cases a strong light intensity and daylight length can increase production of specific compounds such as protein and β-carotene (Seyfabadi et al., 2010).

In general, specific wavelengths of visible light such as blue (420–470 nm) and red (650–680 nm) are considered beneficial to algal cells (Schulze et al., 2014). Blair et al. (2014) used bulbs emitting blue wavelength (475 nm) for the culture of *Chlorella vulgaris* and reported an improved biomass growth as compared to the red (650 nm) and white artificial light. Shu et al. (2011) reported greater lipid content in *Chlorella sp*. illuminated with blue light emitting diodes (LED) compared to red LED. Wang et al. (2007) studied the growth of *Spirulina platensis* as a response to various LEDs, and found higher biomass productivity when grown under red light, (620–645 nm) compared to blue (460–475 nm) and white artificial light (380–760 nm). In the culture of the *Nannochloropsis*, blue LED (470 nm) resulted in better growth than the red (680 nm) and white artificial wavelengths (Das et al., 2011). However, it should be noted that these studies were done with a background fluorescent illumination being used.

These results demonstrate that the use of appropriate wavelengths of visible light is an effective way to enhance algal growth and alter chemical compositions. The effects of wavelength also depend on the species tested. However, one important issue yet to be solved is how to cost-effectively deliver the light with the desirable wavelengths to the large scale cultivation system. The common approach is to use artificial light sources such as specific light bulbs or LEDs (Fu et al., 2012; Wang et al., 2007). However, one must keep in mind that these sources are typically used on systems where significant background fluorescent illumination was present. From this point of view it makes sense that manipulating the solar spectra directly would be most effective. Taking a cost-effective point of view further reinforces that using the natural sunlight is the preferred light sources for large scale cultivation.

A company Wave Tech recently developed a unique filter using nano-scale coating to selectively transmit specific wavelengths from natural sunlight. The material can be tuned to provide different visible spectra allowing certain bands to be more prominent than others. The proprietary material was deposited onto a thin, flexible, plastic substrate. It can also be deposited on other substrates including glass and thick plastics. For the purpose this study, the filter was applied to plastic sheeting due to its versatile form factor. Despite these unique advantages of the filter, the material has not been previously used in algal cultivation system. The objective of this research is to evaluate the feasibility of using this specially designed sheet as light filter to deliver specific wavelength of light to microalgae culture systems and evaluate effectiveness of enhancing cell growth and with specific chemical composition profile by this material.

2. Methods

2.1. Algal strain, medium, and subculture

The microalga *C. vulgaris* (UTEX #236) was used due to its robust growth performance and wide uses in various studies. To prepare seed cultures, the cells maintained in anoxic agar slants were transferred to 250-mL Erlenmeyer flasks containing 50 mL medium. Bold's Basal medium was used in the seed culture as well as the various studies in the light filter-based cultures. The medium pH was around 7.0 before autoclaved at 121 °C for 15 min prior to use. The flasks were placed on an orbital shaker set at 200 rpm and 25 °C with continuous (24 h) illumination (110–120 μmol s^{-1} m^{-2}). Different from the light filter studies which used natural sunlight, the seed culture was performed under the indoor artificial illumination. The cultures were grown for 7–10 days and then inoculated into various culture systems as defined in the later sections.

2.2. Optical light membrane filters

Two variations of light membrane filters (Red and Blue) were used in this work. The membrane is manufactured by a proprietary technology (US patent application #20140154769 A1) and consists of a two mil thick optically clear Type D Mylar substrate. The substrate was coated with layers of metal oxides at nano-scale thicknesses to create the two filters. The red filter is designed to allow the primary transmission of the wavelengths in the red portion of the spectrum (620–710 nm). The Blue filter is designed to allow the primary transmission of the wavelengths in the blue (450–495 nm). Both filters allow variable amounts of the remaining visible spectrum to transmit. The filters may also protect the cells from solar damage and overheating by reflecting portions UV and infrared rays which can cause oxidative stress (Malanga et al., 1997).

2.3. Algal cultivation greenhouse facility

All the algal cultivation experiments were performed in a greenhouse facility located in Iowa State University Biocentury Research Farm in Boone, IA, USA. This greenhouse is made of twin wall polycarbonate with 80% light transparency (Farmtek Solar Star Greenhouse). Natural light was used exclusively throughout the project period. Due to the frequent ventilation of the greenhouse, CO_2 presented in the greenhouse air was at atmospheric levels. Various algal culture systems described below were used for testing the effect of light filters on the algal growth, the duration of the lighting of these culture system depended on the daily/might cycle of the geographical location the greenhouse located.

2.4. Algal cultivation systems

2.4.1. Flask cultures

The flask culture growth was performed in 250-mL Erlenmeyer flasks with 100-mL working volume. The flasks were place on an orbital shaker rotating at 200 rpm. To study the effect of light filters on the flaks culture performance, a box assembled with transparent corrugated polycarbonate panels (30 × 30 × 30 cm) was placed over each shaker to create a growth chamber. To create designated wavelength, one chamber was covered with red filter, the second chamber was covered with blue filter, while the third chamber without any coverage of the light filter was used as a control. The chambers were ventilated (on March 28) by introducing the air from outer environment so the temperature inside the chamber can be maintained at the same level as the greenhouse. The algal culture was performed in three replicate flasks inside each chamber.

To monitor the temperature of the flask culture, an additional flasks holding 100-mL of water was placed into the shaker, an Onset HOBO® temperature probe (Onset HOBO data logger, Bourne, MA) was inserted into the water of this flask to record temperature every hour. The temperature of the chamber was reported as average daily temperature of the 24 records. To monitor the PAR (photosynthetic activity radiation) exposure of the growth cham-

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