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Spectral conversion of light for enhanced microalgae growth rates and photosynthetic pigment production

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HIGHLIGHTS

- Growth/chlorophyll production of microalgae under varied light conditions studied.
- Natural light source modified using various luminescent acrylic sheets.
- Improved growth rates achieved under wavelength-modified light.
- Chlorophyll-a production increased under wavelength-modified light.
- Improved growth under modified natural light reduces need for artificial lighting.

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ABSTRACT

The effect of light conditions on the growth of green algae *Chlorella vulgaris* and cyanobacteria *Gloeothece membranacea* was investigated by filtering different wavelengths of visible light and comparing against a model daylight source as a control. Luminescent acrylic sheets containing violet, green, orange or red dyes illuminated by a solar simulator produced the desired wavelengths of light for this study. From the experimental results the highest specific growth rate for *C. vulgaris* was achieved using the orange range whereas violet light promoted the growth of *G. membranacea*. Red light exhibited the least efficiency in conversion of light energy into biomass in both strains of microalgae. Photosynthetic pigment formation was examined and maximum chlorophyll-a production in *C. vulgaris* was obtained by red light illumination. Green light yielded the best chlorophyll-a production in *G. membranacea*. The proposed illumination strategy offers improved microalgae growth without resorting to artificial light sources, reducing energy use and costs of cultivation.

1. Introduction

Cultivation of photosynthetic microalgae has received increased attention as a potential source of high-value biochemical components such as natural colourants, polyunsaturated fatty acids, proteins and polysaccharides (Chen et al., 2010a,b) as well as being a potential biofuel source or food material. In addition microalgae cultivation has been considered as greenhouse gas mitigation strategy in which solar-driven cells capture carbon dioxide (CO_2) and convert it into organic chemicals (Chisti, 2007).

In photoautotrophic cultivation mode light is the main source of energy and inorganic carbon (such as CO_2) is used as the carbon source (Huang et al., 2010). Photons can be absorbed as nutrient by microalgae cells thus the quality of light in terms of intensity and wavelength is critical for cell growth (Wang et al., 2007).

Specific growth rate and photosynthetic pigment formation are highly influenced by the light source. Up to date the only light sources which have been used for illumination of microalgae cultures and capable of emitting light in specific wavelengths are light emitting diodes (LEDs) (Wang et al., 2007). Long life expectancy, low heat generation and efficient light conversion are the advantages of using a light source such as LED with selective wavelengths (Chen et al., 2010a,b). However, to date no research has been focused on using luminescent acrylic sheets as a tool for selecting certain wavelengths of sunlight for illumination of microalgae cultures. The proposed technique uses transparent thermoplastic polymethyl methacrylate (PMMA) doped with fluorophores against a solar simulator to filter out the undesired wavelengths. Fluorophores contain luminescent molecules and depending on their colours they absorb light at specific wavelengths and re-emit

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them at longer wavelengths. PMMA is a common material for construction of photobioreactors and hence is an ideal material for investigation of growth conditions related to light wavelength variation.

Luminescent acrylic sheets have been used for building luminescent solar concentrators (LSC). LSCs are simple devices used for absorbing incident solar radiation and emitting fluorescence photons (Wilson et al., 2010) and were introduced more than three decades ago for concentrating sunlight (Goetzberger and Greube, 1977; Ho et al., 2012). When the transparent sheet receives the incident light on the front surface, the photons of sunlight are absorbed by fluorescent dye molecules. The dye re-emits the captured photons and transports them towards the edges of the sheet via total internal reflection. The transmitted photons are then collected by solar cells which are attached to the edges of the LSC. A LSC is a "non-imaging" concentrator meaning that it does not use lenses, mirrors or combination of both to collect and concentrate sunlight. Whilst collection of re-emitted photons around the edge of an luminescent sheet is not a practical arrangement for construction of a large object such a photobioreactor, a proportion of the re-emitted photons along with the vast majority of the transmitted photons pass directly out of the face of the luminescent sheet and these can be utilised for algal growth.

There are different types of fluorophores which have been used in luminescent sheets. Three main categories of fluorophores are organic dyes, rare earth materials and quantum dots (Rowan et al., 2008). Photo-stability is an essential factor for performance of organic dyes. The main problem using original organic dyes was that they had poor photo-stability capable of performing for only a few weeks under solar irradiation (Hermann, 1982).

Photo-stability of luminescent sheets with different host materials and fluorophores has been investigated in the literature (Hermann, 1982). New fluorophores with stability of several years under light exposure were later introduced and studied. For instance Lumogen F range dyes (BASF) with great photo-stability and high quantum yields were developed and used for various solar applications including day-lighting system (Sousa et al., 2012). For this study, organic fluorescent dyes were selected as they show great solubility in different types of organic polymers such as PMMA which is widely used in various photobioreactor designs.

As microalgae use sunlight only in the photosynthetic active radiation (PAR) range which includes wavelengths between 400 and 700 nm, using an LSC as a new illumination strategy seems an interesting research topic which is worthy of further investigation. Previously a study focused on optimisation of light quality and quantity for plant growth used fluorescent films with different fluorescent pigments (Chrismadha and Borowitzka, 1994). The results of the study showed that blue fluorescent films enhanced the growth of strawberry fruit whereas red fluorescent films delayed the fruit production considerably. The study suggested that using blue fluorescent films in greenhouses could potentially promote the production of strawberry fruit. Another study reported that red light increased the number of blossoms on rose flowers and was also the favourable light for growth of the tomato fruit due to the morphogenetic reaction of the photosynthetic plants to changes of light conditions (Sukenik, 1991). In the present paper the influence of light source on two strains of microalgae; *Chlorella vulgaris* (green algae) and *Gloeothece membranacea* (cyanobacteria or blue-green algae); by modifying light wavelength range using luminescent LUMINSCENT sheets has been studied. The strains were chosen as geographically local representatives of both prokaryotic and eukaryotic microalgae. The choice of local species minimises any environmental impact in the event of accidental release from large-scale commercial culture. The study investigates the effects of the selected light source on biomass content and photosynthetic pigment production. All aspects of the experiments were designed to mimic local natural growth conditions, to reproduce as best as possible a potential local commercial operation.

2. Methods

2.1. Microalgae strain

C. vulgaris (CCAP 211/79) cultivated in bold basal medium with 3-fold nitrogen and vitamin (3N-BBM+V) was obtained from waste solvent biofilter at Heriot-Watt University, Edinburgh, UK. Medium (3N-BBM+V) was autoclaved and contained the following components: 25.0 g L^{-1} $NaNO_3$; 2.5 g L^{-1} $CaCl_2{\cdot}2H_2O$; 7.5 g L^{-1} $MgSO_4{\cdot}7H_2O$; 7.5 g L^{-1} $K_2HPO_4{\cdot}3H_2O$; 17.5 g L^{-1} KH_2PO_4; 2.5 g L^{-1} NaCl; trace element solution ($FeCl_3{\cdot}6H_2O$, 97.0 mg L^{-1}; $MnCl_2{\cdot}4H_2O$, 41.0 mg L^{-1}; $ZnCl_2$, 5.0 mg L^{-1}; $CoCl_2{\cdot}6H_2O$, 2.0 mg L^{-1}; $Na_2MoO_4{\cdot}2H_2O$, 4.0 mg L^{-1}); Vitamin B_1 (0.12 g Thiaminhydrochloride in 100 mL distilled water. Filter sterile), Vitamin B_{12} (0.1 g Cyanocobalamin in 100 mL distilled water, take 1 mL of this solution and add 99 mL distilled water. Filter sterile).

G. membranacea (CCAP 1430/3) cultivated in blue green algae medium (BG 11) in the bio-processing laboratory of chemical engineering department at Heriot-Watt University, Edinburgh, UK. Medium BG 11 contained the following components: 15 g L^{-1} $NaNO_3$; 4.0 g L^{-1} K_2HPO_4; 7.5 g L^{-1} $MgSO_4{\cdot}7H_2O$; 3.6 g L^{-1} $CaCl_2{\cdot}2H_2O$; 0.6 g L^{-1} Citric acid; 6 g L^{-1} Ammonium ferric citrate green; 0.1 g L^{-1} $EDTANa_2$; 2.0 g L^{-1} Na_2CO_3; Trace metal solution (H_3BO_3 2.86 g L^{-1}; $MnCl_2{\cdot}4H_2O$ 1.81 g L^{-1}; $ZnSO_4{\cdot}7H_2O$ 0.22 g L^{-1}; $Na_2MoO_4{\cdot}2H_2O$ 0.39 g L^{-1}; $CuSO_4{\cdot}5H_2O$ 0.08 g L^{-1}; $Co(NO_3)_2{\cdot}6H_2O$ 0.05 g L^{-1}). Medium BG 11 was autoclaved and the pH was adjusted to 7.1.

2.2. Light sources

150 W Xenon arc lamps (Luxtel's, Ceralux) were driven by a 300 W power supply (PS300-12, Perkin–Elmer). Xenon arc lamps produce a broad illumination spectrum including short wavelengths of ultra violet (UV), visible (PAR) and long wavelengths of infra red (IR) and are commonly used as in solar simulators for the photovoltaic industry and a typical spectrum of a solar simulator can be found in (Vejrazka et al., 2011). The output spectrum of the lamps was measured using a high resolution spectrometer (HR2000 Ocean Optics, USA). The output spectrum of the lamps using the described light filters is presented in Fig. 1.

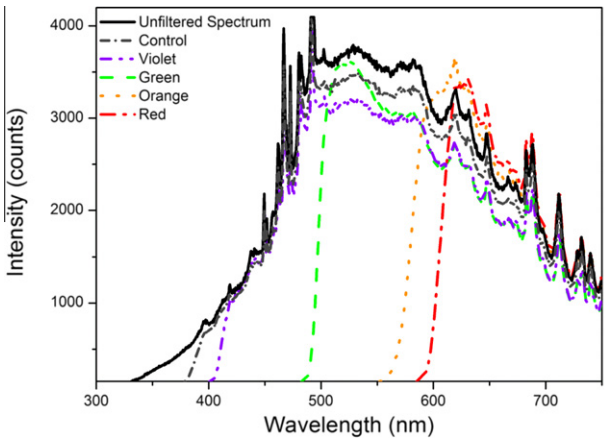

Fig. 1. Graph of light intensity (counts) vs. light wavelength (nm) for different luminescent-filtered xenon light as provided for algal growth. Unfiltered, control (clear PMMA), violet, green, orange and red filters show different wavelength spectra. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)