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Photosynthetic performance of two *Nannochloropsis* spp. under different filtered light spectra

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ABSTRACT

The integration of spectrally selective photovoltaic filters together with microalgae cultivation systems have been previously shown to improve both production efficiency and economics. This means that filtered irradiance incident upon the culture is a portion of the entire solar spectrum. In order to test the viability and optimize such integrated systems, in depth growth and photosynthesis studies of microalgae in such conditions are required. In this applied study, we investigated the impact of spectrally limited light and concomitant reduction in light irradiance on the photosynthetic efficiency of two acclimated *Nannochloropsis* spp. (MUR 266 & MUR 267) through chlorophyll *a* fluorescence and oxygen evolution based measurements under laboratory controlled conditions. Results indicated that (i) no similarities were found between both *Nannochloropsis* spp. in regards of their biomass productivity and photosynthetic performance, (ii) blue light acclimated cultures had remarkably higher concentration of chlorophyll *a* and accessory pigments over biomass due to the lower irradiance, (iii) when photosynthesis was measured on the basis of chlorophyll *a* fluorescence (based on number of photons absorbed per chlorophyll) and oxygen evolution (based on chlorophyll *a* content), pink and white light was most efficient for MUR 266 and MUR 267 respectively. The results of this study clearly indicate that by manipulating the spectral distribution of incident light, photosynthetic efficiency of microalgae can be regulated to optimum levels. The allocation of light spectra (i.e. blue) most efficient for the growth and photosynthesis of the microalgae would allow for the generation of up to 151 W m^{-2} of electrical energy from the remaining unused spectra of sunlight using highly efficient crystalline silicone solar cells.

1. Introduction

Unlike terrestrial plants, the growth of saline microalgae does not rely on freshwater and they can be grown on non-arable land [1,2]. However, in order to fulfil the true potential of microalgae and successfully culture algal biomass at an industrial scale, priority should be first placed on optimizing production efficiency while simultaneously reducing associated costs [2,3].

To achieve this, it is first vital to comprehend the fundamental factors which directly govern the growth, photosynthesis and also biochemical composition of microalgae [4]. Severe limitations in regulating mass outdoor microalgae cultures at optimum photosynthetic efficiencies have resulted in the failure at economies of scale [5]. As a matter of fact, currently the maximum sustained microalgae photosynthetic efficiency (PE) is only around 2%, which is well below the theoretical PE threshold of 12% [6,7].

In general, photosynthesis is governed by several variables. Light (irradiance and spectral quality) is by far the most important component regulating both the growth and photosynthetic performance of microalgae [8,9]. The Earth receives around 3.9×10^6 EJ of total solar energy annually but only a fraction of this free energy is being utilized through photosynthesis and the use of photovoltaics (PV) [10]. In part, this limitation can be attributed by the fact that only specific portions of the solar spectrum ranging between 400 and 700 nm known as the photosynthetic active radiation (PAR) are utilized in photosynthesis

Abbreviations: P-I, photosynthesis against irradiance curves; α, initial slope of the ETR and O_2 evolution based P-I curves; ETR, absolute electron transport rate; ETR_{max}, maximum electron transport rate of ETR versus I curves; *Psi*I, photosystem II; RCII, reaction center of *Psi*I; RLCs, rapid ETR versus Q_{phar} curve; F_q'/F_m', maximum photosynthetic light use efficiency of the open PSII in light-adapted state; LHC, light harvesting complex; P_{max}, maximum rate of photosynthesis from the O_2 evolution based P-I curves; F_v/F_o, relative activity of the water-splitting complex on the donor side of the *Psi*I; PI_{abs}, performance index; PV, photovoltaic; PE, photosynthetic efficiency; OJIP, chlorophyll-*a* fast transient curves; I/P, ratio between the I and P phase of the OJIP curves; W_K, heat stress parameter; XC, xanthophyll cycle; LED's, light emitting diodes; Q_{phar}, photosynthetic usable radiation (PUR) absorbed by the microalgae; LSC, luminescent solar concentrators; IGU, insulating glazing unit.

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(theoretical maximum 12%) [6,7]. On the other hand, commercially available photovoltaics can convert ≈20% of the solar spectrum into electricity making them an ideal candidate for electricity generation [11]. Identifying these shortcomings in solar conversion efficiency, the integration of spectrally selective photovoltaic filters above outdoor microalgae cultivation systems for the full exploitation of available sunlight has been proposed [11]. Parts of sunlight most efficient for the growth and photosynthesis of microalgae (i.e. blue, red and pink) would be filtered and transmitted to cultures through the photovoltaic apparatus while remaining unused spectra; including infrared (IR) and ultraviolet (UV) would be captured and converted to electricity [12].

The proposed PV-microalgae system has been previously validated by the authors through a customized flat plate photobioreactor with its illumination surface consisting of spectrally selective insulated glazing units (IGUs) [13]. The IGU coating allowed the transmission of >50% of visible light while capturing ≈90% of UV and IR radiation through scattering and reflections for collection by an external photovoltaic cell. Modelling of a 20 cm × 20 cm IGU design identified up to 25.2 W m^{-2} electrical power could be generated from the captured portions of incident solar spectra using the spectral photoresponse of a CIS solar cell with 12% conversion efficiency [13].

Moreover, further enhancement of the PV-microalgae system can be potentially realized through the optimization of luminescent solar concentrators (LSCs) for the efficient splitting of light for both purposes [14]. LSCs are commonly constructed of a flat transparent matrix material (i.e. plastic or glass) with photovoltaic cells attached at one or more sides (Fig. 1) [15,16]. The transparent matrix is composed of luminescent particles such as organic dyes, inorganic phosphors or quantum dots embedded in the waveguide region (Fig. 1) [15,16]. Photons of light with sufficient energy to excite the luminescent material are absorbed by the material itself while photons with insufficient energy are allowed to pass through the transparent sheet. The absorbed photons are then re-emitted by the luminescent particles at longer wavelengths which are partially guided towards the photovoltaic cells by total internal reflection in the waveguide region (Fig. 1) [15,16].

LSCs hold great promise as they can be potentially manufactured at low cost, made in different colour, shapes and most importantly their transparencies can be modified [15]. As illustrated in Fig. 1, in an idealized scenario, the selected LSC to be incorporated in the PV-microalgae system would need to transmit photons (most efficient for microalgae, i.e. red or blue) through its waveguide (using spectrally selective filters) while capturing and converting as much of the remaining un-transmitted photons (i.e. green, UV and IR) into electricity through the optimization of luminescent dyes and photovoltaic cells used.

Therefore, in order to optimize such designs and evaluate the viability of the targeted PV-microalgae system, in situ studies assessing the growth, productivity and photosynthetic efficiency of microalgae grown and acclimated under the proposed filtered light spectra conditions are required.

In this study, the effects of different filtered light spectra (mimicking their relative proportion to PAR) on the photosynthetic efficiency of two *Nannochloropsis* was assessed. Commercially available lightning filters (LEE Filters) were used as substitutes for the proposed spectrally selective PV cells. The assumption behind this was that the light spectra transmitted by these filters are to be supplied to algae while un-transmitted portions are to be hypothetically converted to electricity using photovoltaics. In this particular work, we are not concerned on how the remaining unused wavelengths will be collected by the PV cell but are more focussed in investigating the efficient allocation of light spectra for both the microalgae cultivation and electricity production purposes.

Nannochloropsis are widely sought after for their ability to produce various essential commodities such as food, animal feed and high value nutraceuticals. This is mainly due to their high biomass productivity and ability to accumulate large amount of lipid bodies [4,17]. The genus of *Nannochloropsis* is composed of a diverse collection of microalgae that consist of 6 distinguished species [18]. Recent studies on this genus identified significant genetic variability between the different species despite the strong conservation of the 18S rRNA genes [19]. Moreover, it has been reported that notable differences in pigment expression exist among the representatives of this genus, bring forward changes in optical properties and light use efficiency and resulting in the variation of growth and productivity between different species [20]. Therefore, based on the discrepancies between species reported in the literature and our preliminary results, we selected two *Nannochloropsis* spp. with variation in pigment concentration (data not shown) as we expected differences in the growth and photosynthetic response of both these species when acclimated to the different filtered spectral composition. The aim behind this was to identify and select the most compatible species of *Nannochloropsis* for mass cultivation in the proposed PV-microalgae system.

The main objective of this applied study was to identify the most efficient filtered light spectra that can maximize photosynthetic efficiency in both species of *Nannochloropsis*. This scoping study was conducted under laboratory controlled conditions in order to eliminate the effect of undesired environmental variables. Future studies will apply these technologies using outdoor cultivation systems.

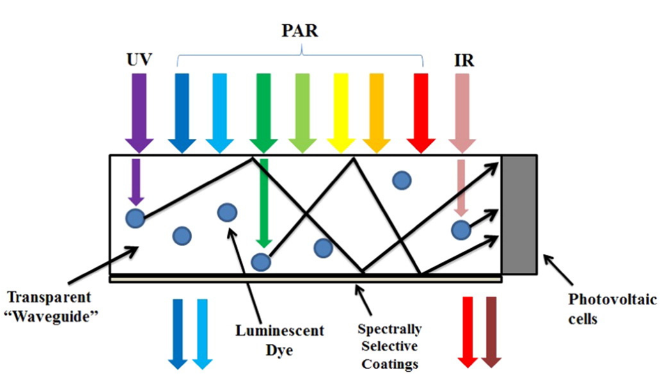

Fig. 1. 3-D schematic view of the proposed luminescent solar concentrator (LSC) to be potentially applied in the PV-microalgae system. In conventional LSCs, incoming sunlight enters the waveguide and is absorbed by the luminophore material. This absorbed light is re-emitted at longer wavelengths which are partially guided to photovoltaic cells integrated on the edge of the LSC cell for the generation of electricity.

2. Materials and methods

2.1. Microalgae strain and culture condition

The marine eustigmatophyceae, *Nannochloropsis* spp. (MUR 266 and MUR 267) used in this study were obtained from the Algae culture collection of Murdoch University. Both species were grown on F/2 medium composed of natural seawater obtained from Hillary's Beach at 33 g L^{-1} NaCl salinity [21]. The seawater was first charcoal filtered (50 μm) and then autoclaved before the addition of sterile nutrients.

Illumination with the different filtered light spectra was achieved by building customized light boxes with its front panel covered by coloured acetate filters [12]. The selected filters were LEE 026 Bright Red (RL), LEE 363 Medium Blue (BL), LEE 124 Dark Green (BGL) and LEE 128 Bright Pink (PL). The irradiance transmitted by each filter was equalized to its relative proportional number of photons found in white light (WL) and was in accordance to the proposed filtered light scenario involving the semi-permeable photovoltaic filters. Halogen lamps were used as the source of illumination as they produce continuous distribution of light, similar to sunlight [22].

The irradiance level of each light treatment is presented in Table 1 while the spectra distribution inside each customized light box was measured using a BLACK-Comet CXR-SR-50 spectrometer (Stellar Net Inc., USA) and is illustrated in Fig. 2. The incident photon-flux density