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Review article

Cultivation of microalgae on artificial light comes at a cost

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ABSTRACT

Microalgae are potential producers of bulk food and feed compounds, chemicals, and biofuels. To produce these bulk products competitively, it is important to keep costs of raw material low. Light energy can be provided by sun or lamps. Sunlight is free and abundant. Disadvantages of sunlight, however, include day/night cycles, changes in weather conditions, and seasonal changes. These fluctuations in irradiance can be prevented by applying artificial lighting. Artificial lighting will not only increase productivity but will also increase costs associated with microalgae cultivation. This cost increase is recognized, but a detailed quantitative evaluation was still missing. The costs and energy balance related to microalgae cultivation employing artificial light was evaluated with a literature study.

We calculated that current application of artificial light will increase production costs by 25.3 $ per kilogram of dry-weight biomass. From these calculations, it was determined that 4% to 6% of energy from electric input is fixed as chemical energy in microalgae biomass. Energy loss and increased production cost may be acceptable in the production of high value products, but in general they should be avoided. Microalgae cultivation programs should therefore focus on employing sunlight.

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Contents

1. Introduction . . . 334
2. Input parameters . . . 334
    2.1. Electricity price . . . 334
    2.2. Light source efficiency . . . 334
    2.3. Biomass yield on light energy . . . 335
3. Results . . . 336
    3.1. Electricity costs resulting from artificial lighting . . . 336
    3.2. Investment costs for artificial light . . . 336
    3.3. Operation and investment costs of a microalgae plant . . . 337
4. Energy balance . . . 337
5. Alternative approaches . . . 337
6. Conclusions . . . 338
Acknowledgements . . . 338
Appendix A. Theoretical maximum WPE . . . 338
Appendix B. From luminous efficiency to wall plug efficiency . . . 338
Appendix C. Calculation of photosynthetic efficiency . . . 339
References . . . 339

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1. Introduction

Microalgae are potential production organisms of bulk food and feed compounds, chemicals, or biofuels [1–5]. In order to competitively produce these bulk products, it is significant to reduce the raw material costs of production [2]. The four major raw materials for microalgae cultivation include phosphorous, nitrogen, carbon dioxide, and light energy.

Light energy can be provided by the sun or with the employment of lamps. This choice is often subject of debate. The exploitation of sunlight as a light source is advantageous in that it is free and abundant. However, it also exhibits certain disadvantages: day/night cycles, changing weather conditions, and seasonal changes. Moreover, all of these factors are location specific. These fluctuations in irradiance levels can be precluded by applying artificial lighting. Continuous and controlled illumination will result in increased productivity as biomass is not dissipated during the night, and artificial lighting can be integrated into the photobioreactor design [6,7]. Volumetric productivity, moreover, can be increased by implementing high density photobioreactors which can be designed with a short light path and high incident light intensity [8,9]. These advantages have led to numerous initiatives where artificial lighting is employed for the production of microalgae biomass [8–10]. The extensive exploitation of artificial light, however, results in investment and electricity costs which will subsequently increase the final production costs [10]. Although the economical disadvantages of artificial light are customarily referenced, the actual costs and the energy balance are disregarded. However, without this information, an assessment of the process economics and sustainability is impossible. Ignoring the energy balance in life cycle analysis over biofuel production can therefore result in flawed discussions [10,11]. The objective was to evaluate the costs and energy balance related to the implementation of artificial light in microalgae cultivation.

2. Input parameters

The final price of microalgal biomass comprises the sum of the costs involved in microalgae cultivation and downstream processing. In this study, the cultivation costs are divided into the costs related to artificial illumination and the estimated normal operating and investment costs of a full-scale photobioreactor plant.

The initial focus will center on the electricity cost required to produce one kilogram of dry microalgae biomass (in dollars per kilogram of dry weight biomass, $ kg-DW^{-1}).[1] In order to calculate this, three values are required; (1) electricity costs; (2) light source efficiency (i.e., the amount of light energy generated for one unit of electrical energy); and (3) microalgae biomass yield from light energy (i.e., the amount of biomass produced per unit of light supplied).

2.1. Electricity price

Industrial electricity prices in the European Union (EU) range between 0.07 $ kWh^{-1} in Bulgaria to as much as 0.20 $ kWh^{-1} on Cyprus with an average of 0.12 $ kWh^{-1} over all EU countries [12]. Industries are subject to these prices when consumption reaches between 10 and 40 GWh year^{-1}. This corresponds to an algae production facility with an approximate annual production of 70 to 280 tonnes of dry microalgae biomass, which is significant considering that the world total microalgae production in 2010 was approximately 5000 tonnes [13].

2.2. Light source efficiency

Numerous types of lamps are commercially available such as fluorescent tubes, high intensity discharge lamps (HID), and light emitting diodes (LED). Ideally, light sources exhibit an extensive wall plug efficiency (WPE) and minimal investment costs. The WPE is the ratio between the radiant flux in watts and the electrical input power in watts. According to Planck's relation, blue light yields less photons per watt when compared to red light (Appendix A). As microalgae can employ all photons in the PAR range (wavelength between 400 and 700 nm) regardless of the energy content of the photon, the WPE does not accurately depict the amount of algae that can be grown per unit of electrical energy. Therefore, in this study, the parameter PAR efficiency is introduced with units in μmol PAR photons per second per watt of energy (μmol-ph s^{-1} W^{-1}).

Based on broad experience in horticulture, three types of lamps are identified as the most promising light sources for microalgae cultivation. The first type, fluorescent tubes, exhibits a PAR efficiency of 1.25 μmol-ph s^{-1} W^{-1} and are mostly exploited in laboratories and plant growth chambers. The second type is HID from which the high pressure sodium lamp with a PAR efficiency of 1.87 μmol-ph s^{-1} W^{-1} is the most commonly employed in horticulture. The third type is LED, which are continuously being improved. Currently, commercially available LEDs exhibit a PAR efficiency of 1.91 μmol-ph s^{-1} W^{-1} [14].

As demonstrated in Table 1, the different lamps are compared according to their PAR efficiency. The results indicate that HID and LED would be the most suitable lamps for microalgae cultivation. Although they exhibit a comparable PAR efficiency, HID remains the preference in horticulture due to the lower investment costs. PAR efficiency of HID, however, has already almost attained its technical maximum while, on the contrary, the PAR efficiency of LED has rapidly increased over the last decade and is continuously improving. Moreover, the price of LEDs continues to decrease [15–17].

Heat production for both, HID and LED lights is in the same order of magnitude as their WPE are similar. LED, however, possess a narrow emission band, and in contrast to HID, there is no emission in the infrared range. The lack of infrared radiation makes cooling of the photobioreactor more convenient as only the light source has to be actively cooled. In regards of HID lighting, infrared light heats the radiated surfaces, which, depending on the working temperature and the ambient temperature, could introduce extra costs in order to cool the systems down.

Three major factors continue to limit the efficiency of LEDs: (1) The refractive indices of the materials employed in the LED differ significantly from air, resulting in total internal reflection of photons and, therefore, light loss. This can be reduced by roughening the LED surface. (2) The WPE is high at low currents but decreases with increasing currents subsequently limiting the light output from an LED. (3) High currents are associated with high temperatures, which can result in degradation of the LED materials, decreasing their lifetime when overheated. The final WPE is determined with the combination of these three main factors [16–18].

Despite these limitations, improvements to the WPE of LEDs remain available. In literature, blue LEDs are reported with a WPE of above 80%, which corresponds to a PAR efficiency of 3.3 μmol-ph s^{-1} W^{-1} (for calculation, see Appendix A). This WPE is achieved with a very low current (8 mA), resulting in a very low output power [18]. This indicates that a significant number of LEDs should be used in order to supply the high output power required to grow microalgae, which subsequently increases the final price of a luminary. In this aspect, LED research is focused on the development of LEDs that produce greater power output in combination with a high WPE. For example, the current PAR efficiency of high power blue and red LEDs are 2.0 and 2.6 μmol-ph s^{-1} W^{-1}, respectively (Table 1) [19]. However, it is anticipated that the PAR efficiency of commercial high power LED lighting systems will eventually increase to 3 μmol-ph s^{-1} W^{-1} in the coming years [15].

Most LED research is focused on developing efficient white LEDs as a replacement for conventional lighting, which consists of incandescent bulbs and fluorescent tubes. A significant number of white LEDs comprise a blue LED with yellow phosphor, which converts a portion of the blue light to yellow light and resulting in white light. In the conversion from blue to yellow light, a loss of energy occurs, decreasing the

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[1] Prices are recalculated from euro to US dollar with the current exchange rate of 1.34 $ €$^{-1}$ (13 June 2013).

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