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Energy efficiency of an outdoor microalgal photobioreactor sited at mid-temperate latitude

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ABSTRACT

This work examined the energetic performance of a 6-month semi-continuous cultivation of *Scenedesmus obliquus* in an outdoor photobioreactor at mid-temperate latitude, without temperature control. By measuring the seasonal biomass production (mean 11.31, range 1.39–23.67 g m^{-2} d^{-1}), higher heating value (22.94 kJ g^{-1}) and solar irradiance, the mean seasonally-averaged photosynthetic efficiency (2.18%) and gross energy productivity (0.27 MJ m^{-2} d^{-1}) was calculated. When comparing the solar energy conversion efficiency to the energy investment for culture circulation, significant improvements in reactor energy input must be made to make the system viable. Using the data collected to model the energetic performance of a substitute photobioreactor design, we conclude that sustainable photobioreactor cultivation of microalgae in similar temperate climates requires a short light path and low power input, only reasonably obtained by flat-panel systems. However, temperature control was not necessary for effective long-term cultivation.

1. Introduction

Microalgae are a promising source of renewable bio-energy: They typically have high areal productivities (Chisti, 2007), can utilise waste water and can be cultivated on land not suitable for conventional agriculture (Clarens et al., 2010). A potential use for microalgal technologies is for the recycling of CO_2 in flue gas produced by the electricity generation industry (Vunjak-Novakovic et al., 2005). In this role, algal growth can be accelerated by the availability of concentrated CO_2, whilst emissions of CO_2 to the atmosphere are offset by producing a renewable biomass fuel.

A key aspect of microalgal physiology, and the main reason they may be favoured over terrestrial crops, is the relatively high efficiency with which they convert solar energy to the chemical energy of biomass (Williams and Laurens, 2010). Calculation of the theoretic maximum efficiency of solar energy conversion (total solar energy to primary photosynthetic products) for microalgae identifies a maximum value of around 10%. However, metabolic activities such as lipid and protein production alone can easily halve this, and measured values are typically 1–3% (Williams and Laurens, 2010).

It is difficult to simulate outdoor conditions in a laboratory, so it is therefore important to gain practical evidence for microalgal productivity in the field, especially in different geographic regions and over sustained periods of time (Scott et al., 2010; Silva et al., 2009). Microalgal productivity varies with geographic location and prevailing weather conditions (Ugwu et al., 2008), and most research on outdoor production has been conducted in regions with a relatively mild climate such as Spain (Camacho et al., 1999), Australia (Moheimani and Borowitzka, 2006), and Israel (Richmond and Wu, 2001). These locations give optimal light and temperature environments leading to high growth rates. However there is also a need to investigate microalgal performance in other locations to assess how suitable such technologies may be. In particular, data for outdoor microalgae production in mid-temperate latitudes is very scarce.

Low-grade waste heat from industrial plant (Shang et al., 2010) may be available at low environmental and economic cost in many industrial scenarios where growing microalgal biomass is being considered. However, a major aspect of photobioreator design which has received little attention is whether or not it is beneficial to control the temperature of microalgal cultivations (i.e. extra biomass energy out *vs.* extra energy in). It is simply not clear from published reports whether supply of heat is essential for cultivation of microalgae and/or provides net benefits, especially in cooler regions of the world (Carlozzi and Sacchi, 2001; Moheimani and Borowitzka, 2006; Shang et al., 2010).

Microalgae have been cultivated in a wide range of engineered systems (raceways, closed photobioreactors), and there is much debate concerning how different technologies compare (Jorquera et al., 2010; Stephenson et al., 2010). Raceway production of algal

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biomass has relatively low energetic and monetary costs, but in turn has relatively low volumetric productivities. Closed photobioreactors, such as tubular systems, may have volumetric productivities around 30 times higher than raceways (Chisti, 2007). However, for bio-energy crops the most relevant comparison is per unit area, and in this case the performance of photobioreactors and raceways may be more comparable (Mata et al., 2010).

From an experimental perspective, the advantage of closed photobioreactors is that they offer an excellent platform for measuring microalgal production in a controlled environment (Ugwu et al., 2008). This avoids problems with contamination (Mata et al., 2010) and allows the maintenance of a stable physico-chemical environment (e.g. pH, nutrients, and low evaporation), which in turn allows accurate and reliable long-term assessments of performance to be made (Kunjapur and Eldridge, 2010; Morweiser et al., 2010). These same advantages may also favour closed photobioreactors for commercial systems.

It is essential that microalgal bio-energy technologies produce more energy than they consume (Das and Obbard, 2011; Jorquera et al., 2010). In particular, recent theoretical work has shown that the apparent productivity advantages of closed photobioreactors may be nullified by the much higher energy requirements of these systems for mixing and circulating cultivations (Stephenson et al., 2010). In fact, closed photobioreactors, in some circumstances, may be net energy consumers rather than producers (Das and Obbard, 2011; Jorquera et al., 2010). However, there is little evidence for the balance between energy production and supply within the same experimental system, and there is an urgent need to ascertain the limits of microalgal productivity, so that cultivation systems can be designed accordingly.

This study examines the energetic performance of a tubular photobioreactor using natural sunlight and no temperature control. It identifies the energy conversion efficiency of a productive, long-term seasonally averaged microalgal cultivation and compares it with the energy invested in circulating and mixing the culture. This allowed the calculation of performance range (energy input) in which cultivation systems must operate in this type of environment. Subsequently, this data was used to define a system which, in terms of power input, is capable of achieving a positive energy return.

2. Methods

2.1. Cultivation

Cultivation was carried out at a south-facing un-shaded plot on at a site located at 53°22′58″N 4°16′01″W (sea level), over the spring and summer of 2010. The freshwater microalga, *Scenedesmus obliquus,* was isolated from a pool at the same location and maintained in the laboratory. The ecotype was selected as it was already adapted to the local conditions, because the species is robust, grows rapidly and has been commonly used for research into mass algal cultures and renewable energy technologies (Mandal and Mallick, 2009; Mata et al., 2010; Silva et al., 2009). The nutrients were supplied (mg L^{-1}) according to Jaworski formulation (Culture Collection of Algae and Protozoa, Oban, UK): $Ca(NO_3)_2{\cdot}4H_2O$ (20), KH_2PO_4 (12.4), $MgSO_4{\cdot}7H_2O$ (50), $NaHCO_3$ (15.9), $EDTAFeNa_2$ (2.25), $EDTANa_2$ (2.25), H_3BO_3 (2.48), $MnCL_2{\cdot}4H_2O$ (1.39), $(NH_4)6Mo_7O_{24}{\cdot}4H_2O$ (1), cyanocobalamin (0.04), thiamine HCl (0.04), Biotin (0.04), $NaNO_3$ (80), $Na_2HPO_4{\cdot}12H_2O$ (36). Nutrients were supplied to the photobioreactor every few days to maintain nitrate > 2 mmol L^{-1}. Dissolved inorganic nitrogen ($NO_3^- + NO_2^- + NH_4^+$) and phosphorus were measured regularly as a check using standard colorimetric methodology. There was no nitrogen or phosphorus limitation throughout the cultivation. The inoculum for the reactor was prepared using three 20 L polythene bag photobioreactors grown and maintained in the laboratory (18 °C, 250 μmol photons photosynthetically active radiation (PAR) m^{-2} s^{-1}).

2.2. Photobioreactor

The experimental photobioreactor (Varicon Aqua Ltd., UK) used to measure productivity consisted of a horizontal tubular system with a 6 m^2 (frontal area) photo-stage placed vertically. The culture was circulated between the photo-stage and tank using a centrifugal pump (Fig. 1). The total system volume was 500 L, the internal diameter of the transparent tubes was 28 mm and water was recycled at a rate of 220 L min^{-1}. The flow pattern was such that the average velocity of the fluid flowing through the transparent tubes was 87 cm s^{-1}. Plastic beads were circulated in the fluid to prevent bio-film build-up on the internal surfaces. The system was operated as a pH-stat at pH 7.0 (±0.2) by addition of pure CO_2. This is the optimum pH for cultivation of many *Scenedesmus* strains (Nalewajko et al., 1997). The bioreactor was operated semi-continuously and nutrients were added to maintain nutrient-replete conditions throughout cultivation. The water used for cultivation was untreated tap water.

2.3. Biomass and biochemical composition

Samples for biomass properties were taken every 1–4 days at 16:00 h, depending upon growth rate. Biomass dry weight and elemental composition (carbon and nitrogen) was analysed as previously described (Hulatt and Thomas, 2010). Biomass higher heating values (HHV) and lipid content were measured using samples taken on days 128 and 169. The biomass higher heating value (HHV) was measured by combusting approximately 1 g (dry weight) samples in a Parr 1341 oxygen bomb calorimeter, which was calibrated using benzoic acid (n = 3), accuracy ± 0.5%. Total lipids were analysed using gravimetric analysis/solvent extraction method: Biomass was prepared by sonication to >99% cell rupture: a Branson 450 Digital Sonifier (Branson Ultrasonics Corporation, Danbury, CT, USA) was used, fitted with a ½ disruptor horn used in conjunction with a 1/8 tapered microtip. The frequency was factory set to 20 kHz. A 30% amplitude (corresponding to 13.5 W per 10 ml sample) was the optimum power to disrupt the cells. After extraction, phase separation and centrifugation, the lipid/chloroform phase was vacuum filtered through Whatman® GF/F filters (0.7 μm nominal pore size) to remove remaining particulates. The protein content was measured using the total elemental nitrogen content, by multiplying the concentration of nitrogen (% mass) by the conversion factor 4.44 (Lopez et al., 2010).

2.4. Temperature and light measurements

Data-loggers (Onset HOBO UA-002-64) were used to record the irradiance incident on the face of the photobioreactor, the scattered and reflected light received by the reverse face, the ambient air temperature in the shade and the temperature of the culture fluid. The scattered light received by the rear face of the photobioreactor accounted for 20.2% of the total irradiance, averaged over the cultivation period. Data-loggers recorded every 5 min throughout the cultivation period and were calibrated *in situ* against a Li-Cor 190SA sensor to convert the light reading to μmol PAR m^{-2} s^{-1}. This was done by measuring values from both instruments positioned side-by-side during various weather conditions and time events (rain to direct sunlight, morning to evening) from March to September (the R^2 value for the light calibration was >0.999). The manufacturer reports temperature accuracy of ±0.54 °C. Where PAR energy was required, measurements were obtained by divid-