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Use of Non-Condensable Geothermal Gas and Geothermal Seawater to Grow Biomass

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ABSTRACT

The geothermal aquifer Blue Lagoon formed roughly four decades ago in a lava field on Reykjanes peninsula in Iceland due to activity of a nearby geothermal power plant. The geothermal fluid of the Blue Lagoon is composed of 2/3 seawater and 1/3 meteoric water (referred to as geothermal fluid), discharged at 240°C from geothermal wells to depths of up to 2000 m. Because of this origin, the BL-geothermal seawater is rich in minerals and salts. Exploitation of the geothermal resources also involve considerable emission of non-condensable gases (NCG), mainly composed of CO_2 (> 90%) and H_2S (~2%). A unique blue-green microalgae species, found in the Blue Lagoon´s ecosystem is being cultivated in a photobioreactor at the Blue Lagoon R&D center, for use as an active ingredient in the Blue Lagoon Iceland skin care products. Being a photosynthetic organism, the microalgae uses light-energy to convert CO_2 into biomass. Originally, the algae were fed on bottled pure CO_2 in a liquid media of geothermal fluid and commercially available nutrient. Three years ago, with aims towards increased sustainability and lower carbon footprint, the high-purity CO_2 was fully substituted by un-purified NCG emitted from the geothermal power plant. In this study, the microalgae´s growth rate was measured in an expanded volume of photobioreactor (3.5 m^3) for a continuous time-span of 5 weeks, using only NCG and geothermal fluid as nutrient sources (in contrast to our previous study where commercial nutrient was added and smaller volume of photobioreactor). A steady growth rate was obtained, indicating that biomass could be sustainably produced using only geothermal resources.

1. INTRODUCTION

1.1. Geothermal Carbon Emission

Carbon dioxide (CO_2) level in the atmosphere has never been higher in the history of human kind and is still growing (Sreedhar et al., 2017). As CO_2 absorbs and emits radiation within the thermal infrared range, it is often referred to as a greenhouse gas. It is further thought to be the single largest cause of the rising global temperature that is now taking place and an estimated 40% of the CO_2 released annually to the atmosphere arrives from the energy sector (Davis et al., 2014). Although geothermal energy is considered a sustainable and environmentally friendly source of energy, its typical exploitation releases considerable amount of carbon dioxide. As an example, the geothermal power plant HS Orka in Reykjanes peninsula, Iceland, utilizes geothermal steam from boreholes to produce 63 MW of electricity and 150 MW of thermal power (as of 2015). Close to 1-2% vol of the steam are non-condensable gases (NCG) emitted into the atmosphere. About 97% vol of the NCG is CO_2 and 2% vol is hydrogen sulfide (H_2S) for the case of HS Orka (Suryata et al., 2010). Around 60×10^3 tons of CO_2 is being discharged this way every year (~32 kg CO_2/MWh). In this paper we describe a use of such NCG to produce biomass.

1.2 Geothermal Fluid – Formation of the Blue Lagoon

The geothermal power plant HS Orka is located on Reykjanes peninsula, Iceland, on highly porous and permeable lava, which allow seawater to percolate deep into their aquifers where it heats up and mixes with meteoric water. Geothermal wells drilled through the lava flows to depths of up to 2,000 m discharge a mixture (here referred to as geothermal fluid) of 2/3 seawater and 1/3 meteoric water with a temperature of about 240°C (Svavarsson, 2014). Most of the spent geothermal fluid is reinjected into the geothermal aquifer (~6×10^6 m^3 annually) but portion of it (~20%) is discharged on the surface where it forms a lagoon - the Blue Lagoon. An overview photograph of the area is shown in Figure 1.

Figure 1: An aerial photograph of the geothermal area in Reykjanes peninsula, Iceland, showing the Blue Lagoon and HS Orka power plant.

1.3 Conversion of Geothermal CO_2 Into Biomass via Algae Cultivation

A number of potential CO_2 sequestration methods have been investigated, but most of them suffer from high processing cost and/or low production rate (Pires, 2011). The most economical approaches/solutions for a large-scale sequestration involve photosynthetic processes in plants and microorganisms in which atmospheric CO_2 is converted to biomass using light energy. Microalgae, a broad category encompassing eukaryotic microalgae and cyanobacteria (prokaryotic) are photosynthetic microorganisms that grow by utilizing solar energy. They can be cultivated to produce biomass for a wide range of applications such as energy, animal feed and human nutrition, agriculture and cosmetics (Markou and Georgakakis, 2011; Svavarsson et al. 2017). Unlike terrestrial crops, microalgae do not produce structural compounds such as cellulose for leaves, stems or roots. Consequently, they can have higher aerial growth rates and their CO_2 fixation efficiency can be up to one or two orders of magnitude higher than that of most terrestrial plants. Additionally, many species can be cultivated in brine water and wastewater not suitable for human consumption or for agriculture (Li, 2008).

1.4 Previous Studies at Blue Lagoon

The physical and chemical characteristics of the Blue Lagoon and its diversity and density of microflora have been previously determined (Petursdottir and Kristjansson, 1996). The lagoon is highly saturated with silica (SiO_2) but the average concentration of silica in the lagoon was measured as 137 mg/kg. Furthermore, concentration of phosphate and nitrate, which are important nutrients for microalgae growth, were found to be 1.4 µM and 5.5 µM, respectively, during summer time. Although the lagoon's high salinity and high levels of continuous silica precipitation would be considered as extreme environment for most living microorganisms, a few types of prokaryotes and cyanobacteria were found. A unique blue-green microalgae species (*Cyanobacteria aponinum*), referred to as the BL-algae, was isolated from the Blue Lagoon´s ecosystem over two decades ago and identified little later (Petursdottir and Kristjansson, 1997). Since its isolation, it has been cultivated in a photobireactor at the Blue Lagoon R&D center, for use as an active ingredient in Blue Lagoon skincare product. Being a photosynthetic organism, the microalgae use light-energy to convert CO_2 and nutrients in its culture medium into biomass.

We have earlier demonstrated that geothermal NCG can be used effectively as a feed for the BL-algae, in a lab-scale and pilot-scale volume (2.8 m^3) photobioreactor and in presence of auxiliary nutrient source (Arnardottir et al., 2015; Svavarsson, et al., 2017)**.** In the present study, the microalgae´s growth rate was measured in slightly larger photobioreactor (3.5 m^3) for a continuous time span of 5 weeks, using only un-purified NCG as a feedstock and geothermal fluid as nutrient sources (in contrast to our previous study where commercial nutrient was added).

In this study it is demonstrated that the nutrient content in the geothermal fluid and use of NCG feedstock is sufficient for a sustainable production of biomass.

2. EXPERIMENTAL PART

2.1. Algae Cultivation

BL-algae, isolated from the geothermal fluid of the Blue Lagoon in Iceland (Petursdottir et al., 2009), was cultivated in a semi-continuous mode in 3.5 m^3 tubular photobioreactor (Phyco-Flow^{TM} from Varicon Aqua, United Kingdom) at 40°C ±2°C at the R&D Center of Blue Lagoon Ltd. An optical micrograph of BL-algae is shown in Figure 2, visualizing its microscopic size.

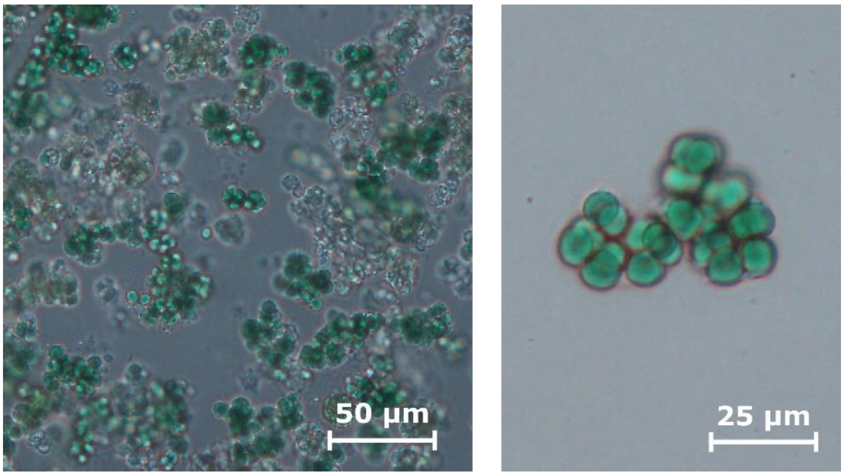

Figure 2: Optical microscope image of BL-algae cultivated in this study at two different magnifications.

The photobioreactor consist of horizontal transparent glass tubes, each being with 28 mm inside diameter and 6 m long, and a 1000 L reservoir tanks. The glass tubes are joined together with semicircles, forming four continuous spirals connected to the reservoir. A constant circulation of the culture between the reservoir and the glass tubes is accomplished by two centrifugal pumps, each of 1.5 kW power. Illumination was provided by light emitting diodes (LED) from Roleadro Galaxyhydro (red and blue ratio of 8:1, 300 W). A photograph of the photobioreactor is shown in Figure 3, illustrating the tubular part of the system. The white box in the upper middle part of the photograph is one of the LED-light sources.

Figure 3: Photograph of the tubular photobioreactor at Blue Lagoon R&D center, used in this study.

The cell density (dry-mass of algae per volume algae culture) was determined daily by vacuum filtering 50 ml algae culture sample through Whatman glass microfiber filter (Sigma-Aldrich, MO, USA). The filter paper was then dried at room temperature for one day and weighted. Geothermal fluid was used as the cultivation media. The pH of the geothermal fluid is on average close to 7.9 but is lowered by the injection of CO_2 and to some extend by the other weak acid, H_2S, present in the gas. A constant pH value of 7.5 ± 0.05 was maintained during cultivation by automatic control of the NCG-flow into the bioreactor. At pH level close to 7.5, the dominating form of CO_2 is the bicarbonate ion, HCO_3^-, which is the preferred form for algae's assimilation of inorganic carbon (Binaghi et al., 2003). We note that due to slight dilution (~8%) with atmospheric air, the composition of the NCG used is altered in respect to the NCG collected in the power plant. Apparently, this dilution takes place within the power plant itself after flashing the geothermal steam and before it enters the pipeline between the power plant and the photobioreactor. Due to this, the concentration of CO_2 in the NCG measures as 90% vol at the photobireactor, compared to 97% vol directly after flashing of the geothermal fluid. This dilution does however not affect the fundamental aspect of the study – a direct use of unmodified geothermal NCG to produce photosynthetic biomass. Once a week, 200 L of the bioreactor's volume was harvested. Subsequently the same volume of fresh geothermal fluid was pumped into the system. The volume of the injected CO_2 was recorded with Bronkhorst (Ruurlo, the Netherlands) Mass-View gas-flow meter (volume normalized to a pressure of 1 atm).

3. RESULTS AND DISCUSSION

3.1. Growth Rate

Prior to the data collection, the algae had been cultivated for two weeks in the same manner, to ensure that the system had gained stability. Cell density (mass of dry algae per unit volume) as a function of day number is shown in Figure 4.

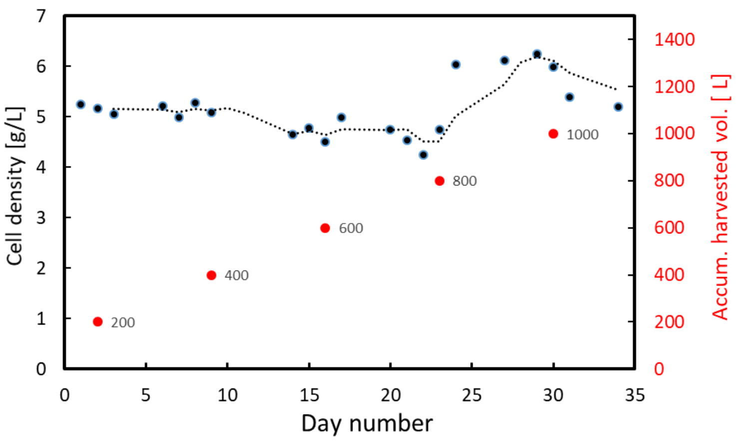

Figure 4: Cell density (black-dotted line, left axis) and accumulative harvested volume (red dots, right axis) as a function of time (day number).

As seen, the cell-density is relatively stable around ~5.5 g/L. In Figure 5, the accumulative harvested dry-mass is shown as a function of day number. The harvested dry-mass was calculated by multiplying the harvested volume with the cell density (black dots in Figure 5) for the same day.

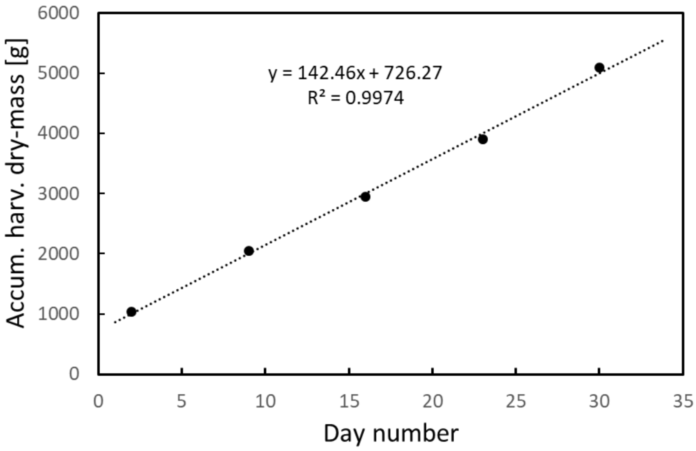

Figure 5: Accumulative harvested algae dry-mass as a function of time (day number).

A very good linear rise in accumulated harvested mass as a function of time is observed, with a regression coefficient (R^2) of 0.9974. The slope of the line tells us that the average growth rate is 142.5 g/day (with a weekly harvested volume of 200 L).

3.2. Conversion Efficiency

The total NCG consumption during this 5 weeks was 17415 L. Based on these values, the conversion efficiency can be derived. Conversion efficiency is here defined as the portion of the supplied gas that is converted into biomass. It is calculated as the ratio between the total mass of carbon (C) in the biomass harvested over a given period of time and the total mass of carbon in the CO_2 injected into the bioreactor over the same period. From the ideal gas law, we get that the mass of C (m_c) in a given volume *V* of the gas-source is equal to:

$$m_C = \frac{VMW_C P_{CO_2}}{RT} \tag{1}$$

where MW_C, P_{CO2}, *R* and *T* denote the molar mass of carbon, the partial pressure of CO_2 injected, the gas constant and the gas temperature (300K), respectively. The concentration of CO_2 in the NCG was measured as 90% vol, which equals to $P_{CO2} = 0.90$ atm. The mass of C in 17415 L is thus roughly calculated as 7643 g. The BL-algae contains ~38% dry-mass of C (H. G. Svavarsson, 2017) which gives us conversion ratio of 25% (7d/week × 5 weeks × 143g/d × 0.38 / 7643 g = 0.25). This is considerable lower than the 42% efficiency we have earlier reported on for BL-algae fed on NCG, using auxiliary nutrition (in a rather similar size tubular photobioreactor) but still surprisingly high. It should be taken into account that there, the harvested volume was much larger, ~1000 L per week, which does increase the efficiency (due to less algae density and consequently less light blockage) although at the expense of the overall efficiency (less algae mass per harvest).

3.3. Nutrient

A supply of nitrogen (N) and phosphorus (P) is critical for the growth of most plants. Its preferred form for assimilation are phosphate (PO_4^{3}) and nitrate (NO_3^-), although some cyanobacteria are known to be able to fix atmospheric nitrogen, N_2 (Markou and Georgakakis, 2011).

Even though the chemical composition of algae species may vary a lot, typical ratios are often given by the biomass formula $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ (Chisti, 2007). In this formula, the mass % of N and P are 6.6% and 1.3%, respectively but values in common blue-green algae have been reported as low as 3% and 0.1% for N and P, respectively. If the lower levels of N and P are considered (N = 3% wt and P = 0.1% wt), the algae would need 30 g N and 1 g P per week in our current set-up. The amount of N and P, brought weekly by the 200 L of the geothermal fluid is much lower (1.4 µM phosphate $P0_4^{3-}$ and 5.5 µM nitrate, NO_3^-). In 200 L there are 5.5×10^{-6}M × 200 L × 14 g/mole = 0.015 g N and 1.4×10^{-6}M × 200 L × 31 g/mole = 0.0087 g of P, much less than needed even though it is assumed that the algae were capable of fixing all the nitrate and phosphate present. Thus, apparently the algae grows on less than 1% of the P needed. The amount of nitrogen is possibly less critical as the BL-algae may be capable of fixing atmospheric nitrogen.

In light of these result, it is to be expected that more frequent harvesting and in more volume would increase the conversion efficiency as more nutrient would be added to the photobioreactor. One solution might by applying constant injection of geothermal fluid and drain the overflow with some filtering.

4. CONCLUSION

A pilot scale production of biomass, using only geothermal seawater (geothermal fluid) and non-condensable geothermal gases as a source materials, was demonstrated. The non-condensable gas mainly contained CO_2 (> 90%) and H_2S (> 2%). In spite of high H_2S content and lack of nutrient, the productivity was stable with time and a CO_2 conversion efficiency of 25% was obtained. The possibility of growing algae without auxiliary nutrient is an important step towards increased sustainability and for further applications of geothermal resources.

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