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Energy-efficient outdoor cultivation of oleaginous microalgae at northern latitudes using waste heat and flue gas from a pulp and paper mill

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ABSTRACT

Energy efficient cultivation is the major bottleneck for microalgal biomass production on a large scale and considered very difficult to attain at northern latitudes. In this study an unconventional method for industrial microalgae cultivation for bio-oil production using pulp and paper mill waste resources while harvesting only once a year was performed, mainly in order to investigate the energy efficiency of the process. Algae were cultivated for three months in 2014 in covered pond systems with access to flue gas and waste heat from the industry, and the biomass was recovered as thick sediment sludge after dewatering. The cultivation systems, designed to manage the waste resources, reached a promising photosynthetic efficiency of at most 1.1%, a net energy ratio (NER) of 0.25, and a projected year-round energy biomass yield per area 5.2 times higher than corresponding rapeseed production at the location. Thus, microalgae cultivation was, for the first time, proven energy efficient in a cold continental climate. Energy-rich indigenous communities quickly out-competed the oleaginous monocultures used for inoculation. The recovered biomass had higher heating values of 20–23 MJ kg^{-1} and contained 14–19% oil dominated by C16 followed by C18 fatty acids. The cultivation season at 59°15′N, 14°18′E was projected to be efficient for 10 months and waste heat drying of the biomass is suggested for two winter months. The technique is proposed for carbon sequestering and energy storage in the form of microalgal sludge or dry matter for later conversion into biochemicals.

1. Introduction

Fossil oil reserves will eventually be depleted and renewable sources of biomass for oil production and other applications must be considered. Algae are highly interesting as feedstock because of their photosynthetic ability to efficiently fix inorganic carbon dioxide (CO_2) and thereby integrate the carbon into organic molecules [1]. However, there are major challenges to overcome to set up an effective cultivation for bulk products, such as polymers, biogas, biodiesel, and bio-oils. These include minimizing material costs, finding product areas where it is possible to reach profitability, and applying energy-efficient cultivation systems that show a positive energy balance during cultivation. The energy cost for pumping, mixing, and harvesting dilute algae solutions is particularly challenging.

It is well documented that the utilization of some industrial waste resources may aid substantially in addressing the challenges to minimize energy and material costs [2]. The pulp and paper (P&P) industry is mainly powered by wood, but still emits large quantities of mainly nonfossil flue gas whose contents include CO_2, SO_2, and NO. Kouhia et al. [3] modeled microalgae production in a biorefinery concept using secondary streams from the P&P industry and found a process that was technically viable. The authors highlight that data from actual pilot tests with microalgae are needed as only few studies concerning algae cultivation using waste resources, including flue gas, from such factories have been conducted.

A substantial upstream energy cost for algae cultivation is the use of fertilizers [4]. Moreover, removal of fertilizers in wastewater treatment is associated with high energy costs and thus combining water treatment and algal biomass production has been considered. Sturm and Lamer [5] studied algae growth in activated sludge wastewater and found that using wastewater nutrients was energetically favorable for microalgae cultivation in open pond systems. Gentili [6] mixed effluents from P&P mills with other more nutrient-concentrated municipal and dairy wastewaters for algae biomass production and showed

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that > 90% of the ammonium and phosphate was removed and that mixtures of wastewater have a good potential for lipid production in microalgae. However, although some studies show successful results, differences in cultivar design, algae species, and cultivation practices complicate comparisons. With the above-mentioned examples in mind, each industry needs to be evaluated separately to find the most suitable cultivation technique for algae.

The purpose of the present study was to test outdoor microalgal cultivation at a P&P mill at high latitude to deliver data on actual biomass production, bio-oil quality, and energy efficiency for the cultivation. Algae were used for sequestering CO_2 in flue gas utilizing waste heat for potential year-round cultivation. By contrast with conventional studies, this study was focused on energy efficiency rather than high productivity. It was based on low-frequency harvesting and pumping because these activities are generally accepted to constitute the major energy costs in algae cultivation systems, as exemplified in the NASA Omega project [7]. Moreover, we deliberately sacrificed biomass quality to gain energy efficiency and therefore, traditional biorefinery concepts where high value products cover the costs for bulk products were abandoned. Our concept avoids investment in continuous harvesting of fresh biomass in order to optimize growth rates and recovery of high value compounds; for example, antioxidants. The cultivation concept was based on circulation in the surface layers and flocculation and settling in the stagnant bottom layers of the ponds.

As cell growth increases exponentially with temperatures up to about 40 °C [8], annual biomass production can theoretically be increased in cold climates by using low-value waste heat. Special algal cultivars were designed to accommodate flue gas and waste heat to minimize energy use for gas delivery and mixing. The designs were inspired by sedimentology and the biogeochemical cycle of algae proposed by Redfield [9] and named after the oil formation process in the Tethys sea 200 M years ago. This sedimentation concept was mimicked in the pond systems, allowing algal biomass to grow in gently mixed surface layers and continuously build up bottom sediments before harvesting. The idea was to make use of solar and/or waste heat drying to harvest a thick sludge or dry (> 95% *w*/w) biomass material.

2. Materials and methods

2.1. Cultivation site

The algae cultivation pilot plant was constructed at the P&P mill of Nordic Paper Bäckhammars Bruk AB, located on the east side of lake Vänern in Värmland, southern Sweden (59°15′N,14°18′E). The plant is a medium-sized mill with a daily year-round 12.9 $m^3\ min^{-1}$ wastewater production with low-grade waste heat having no current application. The flue gas production is large with 145,000 Nm^3 dry gas h^{-1} from the soda boiler and 27,000 Nm^3 dry gas h^{-1} from the bark boiler for 357 days per year (Tarjei Svensen, Nordic Paper Bäckhammars Bruk AB, personal communication).

The cultivation ponds were placed on a layer of gravel on the wasteland next to the treatment plant, which treats water from the P&P process.

2.2. Cultivation equipment

The cultivation site consisted of eight small so-called Tethys ponds (4 duplicates) and for comparison, a single raceway pond. Cultivation in the ponds was replicated other years, but not reported here. The Tethys ponds (inoculation ponds Y1–Y2 and cultivation ponds T1–T6, Fig. 1) were covered pond systems with a cultivation volume of approximately 2 m^3 each, 50–55 cm deep, with a surface area of 3.6 m^2. Mixing and gas distribution (3 W) was provided by a central nozzle. The Tethys ponds had an insulated and water heated floor. The raceway pond (RW) was a covered pond system with an insulated floor and integrated wastewater heating. It had a volume of 6.5 m^3, was 30 cm deep, with a surface area of 21.6 m^2. Mixing was provided by a paddle wheel (10 W; flow 0.3 $m\ s^{-1}$) and gas distribution was provided by five nozzles.

2.3. Flue gas and heating

Flue gas composed of 10–13% CO_2, 55–65 ppm NO_x and up to 3 ppm SO_2 was provided from the soda boiler at the factory. The gas was taken from the base of the chimney, passed through cool water (scrubber) and transported 450 m to the cultivation site. The gas was then distributed evenly into the reactors through a gas valve controlled by the pH in the ponds (see also section 2.6). The paddle-wheel mixing was supplied continuously and flue gas intermittently during the 16 h periods from 06.00 am to 10.00 pm, as the average time between sunrise and sunset during a summer season. Because we did not add any flue gas during the nongrowth period at night to decrease the risk of lowered pH values inducing algal settling, mixing was not conducted at night. Mill wastewater with a median temperature of 40 °C was pumped to the integrated water heating system beneath the construction.

2.4. Water and nutrients

Unsterilized tap water (groundwater of drinking water quality from Kristinehamn municipality) was used to fill the ponds at the start of the cultivation season and for refilling when needed. To supply sufficient inorganic nutrients for the algal cultivation, commercial nitrogen, phosphorous, and potassium (NPK) 20–4–8 lawn fertilizer (Yara) was added. The NPK comprised 20% (*w*/w) total-N (9.2% NO_3–N and 10.8% NH_4–N), 4.3% P, 8.3% K, 1% Mg, and 3% S.

A predissolved amount of 600 g NPK was added to each Tethys pond and 1.8 kg to the raceway pond at the start of the cultivation with no sterilization prior to the addition. To keep the level of ammonium-nitrogen (NH_4–N) above 20 $mg\ L^{-1}$, new NPK was added as needed. In total, 19.275 kg of NPK was dissolved and distributed to all ponds on seven occasions during the season.

2.5. Inoculum

The green freshwater microalga *Scenedesmus obliquus* UTEX 417 (CCAP 276/10, formerly named *S. dimorphus*), originally isolated from Lund in Sweden, was selected as a fast-growing inoculum with lipid production potential. It was precultured in the lab in autoclaved 120 $mg\ N\ L^{-1}$ NPK fertilizer (Hammenhög, Tg Växupp 14–3-15 micro for garden use) dissolved in tap drinking water. The 14% total nitrogen content consisted of 6.2% nitrate–N and 7.8% ammonium–N. To each of four 6 L reactors, 30 mL stock solutions of NaCl, $MgSO_4$, $CaCl_2$, and trace metals and 1 mL vitamin B_1 solution (1.2 $g\ L^{-1}$) and 1 mL vitamin B_{12} solution (0.01 $g\ L^{-1}$) were added. Stock solutions, trace metals and vitamins were prepared according to the commonly used Bold's basal medium with three-fold nitrogen and vitamins added (3 N–BBM + V according to CCAP Culture Collection of Algae and Protozoa, Scotland). Pressurized air of 1 $L\ min^{-1}$ was divided between the four reactors put on magnetic stirrers at room temperature with a light supply (Growth Technology T5HO 4 × 24 W, 90 μmole photons $m^{-2}\ s^{-1}$) during 16 h d^{-1}.

The duplicate inoculum Tethys ponds for the raceway (Y1 and Y2) were supplied with approx. 10 L each of the inoculum on April 3, 2014 (these ponds are not reported further). The small inoculum volume was sufficient for this test considering the long cultivation time and once-a-year harvesting approach, but can be increased in a running large-scale cultivation system.

Different inocula of local strains were used in addition to *S. obliquus* for the T1-T6 ponds. Water samples containing algae were collected at the mill in 2013, grown in liquid 3 N–BBM + V medium, and subsequently spread on 1% agar plates with the same medium. Three well growing strains were morphologically determined according to the