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Resource recycling with algal cultivation: environmental and social perspectives

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A B S T R A C T

Efficient use and recycling of resources by utilizing nutrients of waste water and CO_2 from flue gases are considered through comparing two conceptual systems: a conventional small scale waste water treatment plant (base case) and a waste water treatment plant combined with algae cultivation unit (algae case). The used algae case concept is based on interviews of experts working with algae cultivation in Finland. Hotspots related to the algae case are assessed from environmental perspectives. According to model calculations, in high latitudes effective algae production may be achieved, although the areal production rates are very low in winter. In the algae case concept nutrients of waste water can be more effectively recycled using bio-based chitosan as flocculant. Also energy is produced in the biogas production plant, which increases the resource recycling of the algae case. When considering the energy balance, a positive net energy ratio (NER) >1 is possible to achieve with maximum methane production potential of algal biomass.

1. Introduction

The European Union's policy targets demand an increase in the use of renewable energy. Biofuels, which are one option for renewable energy sources, can have a significant role in the energy market in the future (Manninen et al., 2013). In recent years, there has been a growing interest in microalgae cultivation, although the concept of using algae as a fuel has existed since the 1950's (Hu et al., 2008). Microalgae has proved to be a promising feedstock for biofuel, such as biodiesel production, but it has not yet reached its full potential (Alcántara et al., 2013; Lakaniemi et al., 2013). LCA studies have shown that algal biofuels can be environmentally better compared to fossil fuels, but they are not yet so attractive economically (Singh and Olsen, 2011).

Microalgae are an interesting alternative to terrestrial plants, because there is no requirement for soil fertility and thus their cultivation does not directly compete with agriculture (Clarens et al., 2010; Williams and Laurens, 2010). They can have a high growth rate and they may double their biomass within 24 h because of their high photosynthetic efficiencies (Chisti, 2007; Lakaniemi et al., 2013). Consequently, less land would be needed to produce a given amount of biodiesel from algal biomass than from traditional energy crop (Chisti, 2007; Singh et al., 2011).

The main techno-economic obstacles to commercial microalgae biofuel applications are related to: CO_2 demand and fertilizer (mainly nitrogen and phosphorus) use during up-stream processes (Clarens et al., 2010); the light supply in cultures (Blair et al., 2014); the energy consumption during cultivation, harvesting and oil extraction processes (Razon and Tan, 2011); and water usage (Yang et al., 2011). In order to avoid using pure CO_2, chemical nutrients and fresh water, waste streams such as CO_2 from flue gases and nutrients from waste water can be used in the cultivation phase (Mata et al., 2010; Park et al., 2011; Soratana and Landis, 2011). This would decrease both environmental impacts and economic costs and therefore developing systems utilizing waste streams from other industries is desirable.

Algae based biodiesel production has been widely studied (e.g. Khoo, 2009; Kim et al., 2013; Komolafe et al., 2014). To decrease energy consumption of biodiesel production, the coupling of anaerobic digestion (i.e. biogas production) in the biodiesel production process has been suggested. The methane produced from anaerobic digestion process can be used to produce electricity, which in turn can be used in other processes to decrease the requirement for an external energy source (Harun et al., 2011; Sialve et al., 2009). The biogas production also offers a solution

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for the management of large quantities of residual biomass after lipid extraction (Sialve et al., 2009).

Studies of microalgae cultivation outdoors have mostly been conducted in regions with relatively mild climates, because they have an optimal light and temperature condition, leading to high growth rates. However there is also a need to investigate microalgal performance in other regions to assess whether such technologies would be suitable there (Hulatt and Thomas, 2011; Williams and Laurens, 2010).

The aim of this article is to assess the potentials and challenges of a conceptual small scale waste water treatment plant combined with algae pond concept taking into account the following aspects: 1) waste water and CO_2 from flue gases as inputs for algal cultivation; 2) use of the algal biomass as a feedstock for biogas production, and 3) use of the digestate from biogas production as fertilizer. A novel aspect that we address is our case study which is situated in Finland with a cold and dark winter season. Our study was constructed on the basis of expert interviews and literature values for algal production estimates. We have evaluated the feasibility of this technology from the environmental point of view under climatic conditions found at high latitudes, in combination with social perspectives identified from expert interviews (Section 2.1).

2. Methods and assumptions

The methods and assumptions section consists of two parts. In the Section 2.1, the methods and views related to expert interviews are presented. The Section 2.2 contains the assumptions essential for the environmental perspective calculations.

2.1. Expert interviews

2.1.1. Method

In order to assess the possibilities of producing algae in Finland, we interviewed eleven experts working with and developing algae production there. Expert interviews are a good method of exploring a new field, as perceptions regarding it would be difficult to obtain otherwise due to lack of public knowledge on the issue. Experts can be seen as ‘crystallization points’ for knowledge regarding particular field and base their opinions on their expertise (Bogner et al., 2009). This way they provide valuable information on issues affecting the development of a new field. However, they only provide their perceptions on the matter, and these cannot be generalized to present the population or be regarded as unquestionable facts.

The interviewees represented different companies and research and development organizations (Table 1). They were selected using a snowball method, where the interviewed persons were asked to name other relevant algae experts for interviewing. The rather small number of interviewees is explained by the relatively small number of commercial algae cultivation experts in Finland and hence, can be regarded as well representing the expert perceptions on the field. The interviews were qualitative and thematically structured (Warren, 2001). The themes included the experts' own work and experiences regarding algae production, their perceptions on the potential applications, benefits and critical development points related to algae production. The interviews lasted from 45 to 120 min and they were recorded and transcribed. The interviews were analyzed using qualitative content analysis (Silverman, 2006), where the responses were classified summarizing the visions for benefits and barriers, suitable production systems and critical development points. In order to gain a deeper understanding of the social issues involved in algae production, the data was analyzed further using qualitative frame analysis (Scrase and Ockwell, 2010): the different ways the respondents regarded the potentials and barriers related to algae production in Finland were scrutinized (Section 3.1).

Table 1
Interviewees.

Organization	Number of interviewees
Finnish universities	3
Other research organizations	1
Regional development agencies	1
Small and medium sized companies	3
Large companies	3

2.1.2. Potentials of algae production

All the experts regarded algae production as a highly interesting emerging field. The benefits of algae production include for example the availability of multiple products, rapid growth and biomass production potential, and low land and water use requirements (Table 2). The possibility of combining several beneficial functions like waste water purification, nutrient recycling and carbon capture in algae production systems were also considered as major benefit. Globally, the core interest for algae research and development was seen in its potential as a renewable energy source. According to the interviews the EU's goals of increasing the utilization of renewable energy in general and biofuels more specifically, combined with developed and anticipated sustainability criteria for biomass have been especially important regarding algae. Biofuels produced using algae seem to meet the criteria excellently and even provide for a multifold carbon accounting as a biofuel.

From the Finnish experts' perspective, large-scale algae cultivation for energy (biodiesel) production was not regarded as a feasible objective (Table 2). The climatic conditions were seen as more favorable in countries closer to the Equator, where algae cultivation results in considerably lower energy consumption in terms of artificial lighting and heat. In Finland, the experts saw algae production as more feasible if it could be combined with existing industrial facilities or waste water treatment systems with biogas plants. In these systems algae would be produced utilizing industrial effluents: process heat, nutrients from waste water and carbon dioxide from exhaust gases. Algae production would contribute to several functions, such as waste water management, nutrient recycling and even carbon capture, renewable energy production being only a side function.

2.2. Case study description

The basis for our case study (called as the algae case in this paper, Fig. 1b) is a conceptual small-scale waste water treatment plant (WWTP), representing an average plant of the 13 selected Finnish plants. The average discharge to those selected plants is 482 m^3 d^{-1} and organic load as BOD_7 content 234 mg L^{-1} (Table 3). The population equivalent (PE) is calculated according to Finnish Urban Wastewater Act as 70 g d^{-1} of BOD_7 per person, which gives average PE as 1611. Activated sludge process is a typical treatment process used in the WWTP. In the conventional small-scale WWTP, waste water sludge is typically composted and used in the landscaping (called as the base case in this paper, Fig. 1a). In addition, we assume that in the same area of the WWTP, a biogas plant exists. The biogas plant can utilize agricultural waste and sewage sludge from municipal WWTPs to produce biogas in an anaerobic digestion process. Biogas is led to the combined heat and power (CHP) unit next to biogas plant to produce electricity and heat.

The algae case study is defined in accordance with the interviewees' suggestions for a possible algae production system in Finland. We selected the most popular and currently available