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Microalgal biomethane production integrated with an existing biogas plant: A case study in Sweden

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HIGHLIGHTS

- Microalgae cultivation can be integrated with an existing biogas plant.
- The integrated system could be realized in some cold regions during the warmer half year.
- Greenhouse heating cannot be employed during the cultivation to attain net energy.
- Algal biomethane production would have a net energy ratio of 1.54.
- The system could increase the annual biomethane output by 9.4% for the case of Växtkraft biogas plant (Sweden).

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ABSTRACT

Microalgae are considered as potential sources for biodiesel production due to the higher growth rate than terrestrial plants. However, the large-scale application of algal biodiesel would be limited by the downstream cost of lipid extraction and the availability of water, CO_2 and nutrients. A possible solution is to integrate algae cultivation with existing biogas plant, where algae can be cultivated using the discharges of CO_2 and digestate as nutrient input, and then the attained biomass can be converted directly to biomethane by existing infrastructures. This integrated system is investigated and evaluated in this study. Algae are cultivated in a photobioreactor in a greenhouse, and two cultivation options (greenhouse with and without heating) are included. Life cycle assessment of the system was conducted, showing that algal biomethane production without greenhouse heating would have a net energy ratio of 1.54, which is slightly lower than that (1.78) of biomethane from ley crop. However, land requirement of the latter is approximately 68 times that of the former, because the area productivity of algae could reach at about 400 t/ha (dry basis) in half a year, while the annual productivity of ley crop is only about 5.8 t/ha. For the case of Växtkraft biogas plant in Västerås, Sweden, the integrated system has the potential to increase the annual biomethane output by 9.4%. This new process is very simple, which might have potential for scale-up and commercial application of algal bioenergy.

1. Introduction

Microalgae are considered as potential sources for biodiesel production due to the higher growth rate than terrestrial plants. However, the large-scale application of algal biodiesel would be limited by the downstream cost of lipid extraction and the availability of water, CO_2 and nutrient [1]. To produce 1 t algae biomass, about 1.8 t CO_2 70 kg N, 10 kg P and 8 kg K are required [2,3]. The downstream processes of biomass drying and lipid extraction would take up 50–90% of the overall energy consumption [4,5]. It is therefore worth to explore simple and robust processes for the energy utilization of algae biomass [3].

The technology of anaerobic digestion is applied to convert organic waste directly into biogas. Many countries are now advocating energy crop planting to attain more biogas feedstock. For example, 29% (dry basis) of the feedstock to the Växtkraft biogas plant in Västerås Sweden is ley crop produced from 300 ha arable land [6]. Certainly, algae biomass could be used to produce biogas. This idea was first proposed by Golueke et al. [7] in 1957, and is still being investigated today. The study by Yuan et al. [8] showed that anaerobic digestion is a promising method to treat the blue algae biomass from eutrophic lakes. In addition, some scientists [9,10] from countries with cold climate are also interested in algae

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Nomenclature

LCA	life cycle assessment
GHGs	greenhouse gases
CO_2e	CO_2 equivalent
NER	net energy ratio
PBR	photobioreactor
DM	dry matter
VS	volatile solid
LD	liquid digestate
SD	solid digestate
TN	total nitrogen
TP	total phosphorus
TK	total potassium
WWTP	wastewater treatment plant

cultivation for biogas production. As shown in the research by Collet et al. [3], the coupled process of algae cultivation and succeeding biogas production is a better option compared to algal biodiesel production. However, it still needs fertilizer supplements and the investment of biogas infrastructures [3].

A possible solution for overcoming the high cost is to integrate algae cultivation with an existing biogas plant, where algae can be cultivated using the discharges of CO_2 and digestate as nutrient input, and then the attained biomass can be converted directly to biogas or biomethane by the existing infrastructures. Until now little is known about such integrated system, and there is also no report on the evaluation of algae cultivation in cold climate. This study is to evaluate the performance of above mentioned system based on the case of the Växtkraft biogas plant in Västerås, Sweden. Energy and GHGs balances of algal biomethane production were assessed in the perspective of life cycle, and comparison with ley crop was also conducted.

2. Data and methods

2.1. The existing biogas plant

The existing biogas plant Växtkraft in Västerås (59.61°N, 16.51°E), Sweden, started in the summer of 2005 [11]. The plant can treat about 14,000 t municipal organic waste, 4000 t liquid waste (grease trap removal sludge), and 5000 t ley crop, and produce 54,000 GJ biomethane and 1979 t CO_2 annually (Table 1). If including the upgrading of the raw biogas from WWTP, the productions of biomethane and CO_2 are 82,800 GJ and 3034 t, respectively. After pretreated (i.e. shredding, sieving, mixing, suspending) and sanitized at 70 °C for at least 1 h, the wastes are co-digested with ley crop at 37 °C [6]. The digestate is separated into a solid and a liquid fraction by decanting centrifuges and stored separately, and then transported to farm land for ley crop plantation of 300 ha [12]. The average distance from digester to storage site is 17 km [11,13]. The ensilaging of harvested ley crop is conducted in the plant, and takes up about 1 ha land. The produced biogas is upgraded to biomethane for vehicle fuel [6,12].

2.2. Studied integrated process

In Fig. 1, the suggested layout of the integrated plant in this study is shown. Due to the cold climate conditions, algae should be cultivated in a photobioreactor (PBR) in a greenhouse, using the discharges of CO_2 and liquid digestate from biogas process as nutrient input. The algae suspension in the PBR could be concentrated by the methods of natural setting and centrifugation, and then the dry matter (DM) of the attained algae slurry could reach at 6.6% [3,14], which is about the same DM content as that of the digester inflow of the existing biogas plant. The supernatant during concentration is recycled to the PBR, and the concentrated algae slurry can be put into the existing digester directly, and co-digested with current feedstock. After the raw biogas is upgraded to biomethane, the byproduct CO_2 is recycled to the PBR.

A flat-plate PBR, which is one of the most common reactors, is employed, since it consumes less energy than a tubular reactor [16]. According to reference [16,17], the PBR unit is designed as follows: height 1.45 m, working height 1.25 m, and depth 0.1 m (Fig. 2). The two biggest surfaces of the PBR are made by glass, while the other surfaces could be of metal material. Several PBR units are stacked vertically into two layers to enhance the utilization efficiency of the greenhouse, and they are located one meter apart from each other to avoid shading [2,16]. Using such PBR system, 23,200 m^2 glass and 4400 m^2 land are required for an algae cultivation of 1000 m^3.

2.3. Life cycle assessment

The life cycle boundary used in this study is from feedstock production to biomethane sold at the gate of the biogas plant (Fig. 1), including the stages of cultivation, concentration, biogas production, biogas upgrading, and transportation. Because the main mate-

Table 1
Data of Växtkraft biogas plant in Västerås, Sweden [6,12,14,15].

Feedstock		DM%	Percent%[a]			
Organic waste, t/a	14,000	30%	68.7%			
Liquid waste, t/a	4000	4%	2.6%			
Ley crop, t/a	5000	35%	28.6%			
Output		DM[b]	TN[b]	TP[b]	TK[b]	NH_4-N/TN
Liquid digestate (LD), t/a	89,131[b]	2.5%	0.367%	0.025%	0.183%	65%
Solid digestate (SD), t/a	6500	25%	0.868%	0.180%	0.204%	28%
Digestate (LD + SD), t/a	95,631[b]	4.4%	0.431%	0.036%	0.177%	56%
LD / SD (w/w)	13.7	1.4	5.8	1.9	12.2	
CO_2, t/a[b,c]	1978.9					
Biomethane, GJ/a[c]	54,000	1,597,826 m^3/a				

[a] Feedstock percent on DM basis.
[b] Estimation according to the Ref. [14].
[c] 82,800 GJ biomethane and 3034 t CO_2 in total can be produced annually, if including the upgrading of the raw biogas from WWTP.