Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Life cycle energy demand from algal biofuel generated from nutrients present in the dairy waste

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ABSTRACT

In the USA, approximately 6 million tons of nitrogen and 1 million tons of phosphorus are being produced as a waste stream from the dairy operations. The main aim of this research was to estimate the potential of algal biofuel production, using waste nutrients present in the dairy waste, as well as performing a life cycle assessment to estimate the energy requirement of produced algal biofuel. Four different scenarios for algal biofuel production were simulated using different combinations of the following processes (i) algal-biodiesel-production, (ii) anaerobic-digestion (AD), (iii) pyrolysis and (iv) enzymatic-hydrolysis. Scenario 1 consists of AD and algal biodiesel production. Introduction of pyrolysis in the second scenario decreased biofuel production by ~6% in the initial cycle and gradually increased to 25% in the later cycles. In the third scenario, biomass liquefaction through enzymatic hydrolysis was introduced to recover nutrients and sugars from the sludge generated from the AD process. Recovered nutrients and sugars were used for additional algal biodiesel production. Remaining sludge after the biomass liquefaction was applied on the agricultural land. As compared to the 1st scenario, further processing of the sludge through liquefaction increased the overall bioenergy production marginally. In the fourth scenario, biomass left after liquefaction was further processed through pyrolysis. In the fourth scenario, a 38% increase in the energy production was observed versus the 1st scenario. Additional energy production (compared to 1st scenario) through pyrolysis (Scenario 2) required additional 1.5 GJ of energy per GJ of energy produced and showed little variability. Additional energy production through the 3rd and the 4th scenario is not energetically favorable as compared to the 1st scenario. With respect to the 3rd scenario, energetically favorable additional energy can only be produced by the 4th scenario. Life-cycle energy-demand of the produced biofuel was varied from 0.35 to 0.68 GJ/GJ of energy produced. This study estimated that using dairy waste at a maximum of 3.14 billion GJ bioenergy could be produced.

Keywords: Dairy Manure; Life cycle analysis; Energy demand; Anaerobic digestion; Pyrolysis

1. Introduction

Concerns over rapidly depleting fossil energy sources and escalating greenhouse gas emissions have resulted with increase in interest on alternative energy sources. Biofuel is compatible with existing automobile and fuel infrastructure and is a renewable alternative to fossil fuels.

Several life cycle based studies have highlighted the various advantages and disadvantages of algae based biofuel. Lardon et al. (2009) first indicated that dewatering and drying were the main bottlenecks to make algal biofuel energetically favorable. To reduce the energy demand of dewatering and drying, lipid extraction from wet algal biomass was proposed, instead of extracting lipid from dried algal biomass (Vasudevan et al., 2012; Sills et al., 2013). To circumvent the lipid extraction related energy demand, hydrothermal liquefaction of wet algal biomass was also used to produce energetically favorable liquid fuel (Boer

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http://dx.doi.org/10.1016/j.spc.2016.07.001
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et al., 2012). Some researchers proposed to reduce the energy burden of dewatering and drying, by processing the residual biomass further for biofuel or valuable products formation. Therefore, several studies emphasized on residual biomass management to make algal biofuel energetically and environmentally attractive (Brentner et al., 2011; Chowdhury et al., 2012). Even though, most of the researchers conclude that environmentally benign and energetically favorable algal biofuel production can be possible, economic analysis of algal biofuel shows that virgin nutrient based biofuel production is not economically viable (Resurreccion et al., 2012). Batan et al. (2010) elaborated the critical issue with nitrogen (N) and phosphorous (P) for biofuel production, especially phosphorous as resources of phosphorous are already scarce (Cordell et al., 2009). In that context, waste nutrient (N, P) based biofuel production can reduce our dependency on the virgin nutrient for biofuel production.

Chowdhury and Freire (2015), reported that in the USA, 6 million tons of nitrogen and 1 million tons of phosphorus are being produced as a waste stream from the dairy operation. Dairy waste contains hormones and pharmaceuticals (Zheng et al., 2008; Burkholder et al., 2007) and runoff from the dairy operation can degrade the water quality of the receiving water bodies (Donner and Kucharik, 2008). Therefore, recovery of dairy waste for biofuel production can reduce the environmental burdens associated with dairy waste and also produces new economic opportunity in the rural areas. Zhang et al. (2013) reported that economically viable algal biofuel could be produced from the algal biomass grown in the diluted dairy waste. Chowdhury and Freire (2015) reported a few experimental investigations which demonstrated successful uses of waste nutrients for producing algal biomass containing low to medium lipid. Even though, algal biomass produced from the waste nutrients (N, P) has low lipid content, energetically favorable and environmentally benign biofuel can be produced if appropriate biomass processing can be integrated in the biofuel production process train (Chowdhury et al., 2012). Recently, Zhang et al. (2013) showed that enzymatic hydrolysis solubilized a part of the nutrients and carbohydrate present in the algal biomass. Therefore, incorporating enzymatic hydrolysis in the residual biomass management can further reduce our dependency on the virgin nutrients (N, P) for algal biofuel production.

Integrating anaerobic digestion, enzymatic hydrolysis and pyrolysis for residual biomass processing would increase the bioenergy production and also increased nutrient recovery and recycling. Chowdhury and Freire (2015) assessed four scenarios for producing bioenergy from dairy manure as a source of nutrients for algal growth, and showed that integrating extensive residual biomass processing would produce more bioenergy. However, most of the time, producing excess bioenergy is not energetically favorable. This paper builds up on the scenarios reported by Chowdhury and Freire (2015) and evaluated primarily the variability in energy demand of produced biofuel in different time scale. This variability was primarily introduced due to increased effort of recovering nutrients with progress of operation through various processes such as pumping, anaerobic digestion, and enzymatic hydrolysis. Recycling of nutrients through anaerobic digestion, enzymatic hydrolysis, also consumes energy. Hence, as mass of the recycled nutrients increases energy demand by the produced biofuel also increases.

2. Goal and scope definition

Dairy operations in the US produce milk and meat as core products; in addition these operations also produce waste streams rich in nutrients (N and P). Four different scenarios were constructed using various combination of (i) anaerobic digestion, (ii) algal biodiesel production using dairy nutrients, (iii) pyrolysis, and (iv) enzymatic hydrolysis (Fig. 1). Details about each scenario are given later. An LCA approach was also used to estimate primary energy demand (GJ) from the produced biofuel using a cradle to gate boundary. After estimating the bioenergy production, the net energy ratio (NER) was estimated. NER is a ratio expressing the relationship between the primary energy required and bioenergy generated. The functional unit of the analysis was 1 GJ of energy produced in the form of biofuel. Dairy waste collection and transport to the treatment facilities were not taken into consideration in this study.

Development of a system boundary is an integral part of the goal and scope definition of the LCA approach. Because of insignificant contributions to the whole life cycle impact, construction of different components such as an algal pond, anaerobic digesters has not been taken into consideration (Ruether et al., 2005). Modeling details of the associated processes and integrated systems are available elsewhere (Sadhukhan et al., 2014) Therefore; the main component that requires producing biofuel is energy in the form of electricity and heat. Heat energy was supplied through biogas and natural gas. Electric energy was taken from the grid (average energy mix of the US was used) (Chowdhury and Freire, 2015).

2.1. *Scenario description and assumption*

Nutrients remain in the bound state in the manure hence, solubilization of nutrients need to be done first for using the solubilized nutrients for algal biomass production. In all the scenarios, anaerobic digestion was used for solubilization of nutrients, and, production of energy rich biogas. Four different scenarios were constructed and process flow diagrams and system boundary of the scenarios are shown in the Fig. 1. Four types of processes have been incorporated to develop these scenarios i.e. (i) anaerobic digestion, (ii) growth of algae and subsequent biodiesel production, (iii) enzymatic hydrolysis of biomass and (iv) pyrolysis. Pertinent data used in this study are taken from Chowdhury and Freire, 2015.

2.2. *Allocation procedure*

There are several allocation procedures available to allocate energy, water and environmental impacts associated with byproducts/recycled materials. In this study, biofuel and residual biomass or biochar were produced. Following commodities produced during biofuel production was allocated according to the following methodology:

(i) excess heat as biogas produced from the biofuel production process train was assumed to be used as a substitute of natural gas. If produced biogas was not sufficient to dry the algal biomass, natural gas was used for drying.

2.3. *Calculation procedure*

Number of cows and steer present in the US were collected from Chowdhury and Freire (2015). Duration of each cycle

Please cite this article in press as: Chowdhury, R., Franchetti, M., Life cycle energy demand from algal biofuel generated from nutrients present in the dairy waste. Sustainable Production and Consumption (2016), http://dx.doi.org/10.1016/j.spc.2016.07.001