Applied Energy 161 (2016) 300–308

Contents lists available at ScienceDirect

Applied Energy

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

Life cycle assessment of algae biodiesel and its co-products

Edgard Gnansounou *, Jegannathan Kenthorai Raman

Bioenergy and Energy Planning Research Group (BPE), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland

HIGHLIGHTS

- Protein and succinic acid could be valuable co-products for algae biodiesel industry.
- Co-products from algae have less environmental impact than reference products.
- Succinic acid production from algae has significant influence on impact reduction.
- Protein extraction from algae has high energy demand.

ARTICLE INFO

Article history:
Received 16 June 2015
Received in revised form 24 September 2015
Accepted 5 October 2015

Keywords:
Life cycle assessment
Algae biodiesel
Protein
Succinic acid
Co-products
Biorefinery

ABSTRACT

There is a need to explore alternative energy sources to meet the future energy demand in a sustainable way. Algae could be a potential feed stock for biodiesel and other co-products such as animal feed and chemicals. Life cycle assessment (LCA) of such production system has to be assessed before any implementation at commercial scale. In this context, a prospective LCA of algae biorefinery considering selected multi-products (biodiesel, protein and succinic acid) was carried out to estimate the environmental impact compared to a reference system. LCA results revealed less CO_2 emissions and land use for biodiesel, protein and succinic acid production system compared to that of only biodiesel and protein production system from algae. The impact reduction was even more when compared with conventional diesel, soy protein and fossil based succinic acid system. A higher carbohydrate composition in algae favors less CO_2 emissions and fossil fuel consumption in the algae system compared to that of the reference system.

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1. Introduction

Global warming is a major issue that will lead to several harms such as extreme weather conditions and sea level rise. Increase in fossil fuel use results in high carbon dioxide emissions and contributes significantly to global warming. Measures to reduce fossil fuels use are under way for the past few decades via renewable energy development such as solar, wind, hydro and biofuels. While other energy forms could replace the fossil fuels in several sectors, higher fossil energy use in transport sector could only be reduced by few substitution options among which biofuels are the most promising. With increase in policy reforms in the transport sector to replace fossil fuels by biofuels, there has been a tremendous interest in the development of biofuels across the world for the past two decades [1]. Biofuels include bioethanol and biodiesel produced from edible biomass such as sugarcane, corn, rape seed, palm etc., and non-edible biomass such as lignocellulosic residues and algae. However, biofuels production from edible biomass is believed to be one of the reasons for food price hike in recent years [2] and therefore much research focus is given to non-edible based biofuels.

Biodiesel could be produced from any type of oil such as soybean, corn oil, palm or algal oil. However, algae oil is more attractive because of the algae capacity to yield more oil without requiring large area of arable lands, scope for better strain improvement and the capacity to enhance the value through co-products [3]. Indeed, production of only biodiesel from algae would not be economically feasible due to its relatively low value. Therefore much research efforts are being dedicated to algal multi-products system [4,5]. Algal biorefinery capable of producing diesel, ethanol as well as higher value added products could be an option to address the economic challenge. Several value added products could be produced from algae such as animal feed, health care products, cosmetic products and biochemicals [6].

* Corresponding author at: Bioenergy and Energy Planning Research Group, EPFL ENAC IIC GR-GN, GC A3 424 (Bâtiment GC), Station 18, CH-1015 Lausanne, Switzerland. Tel.: +41 216936027; fax: +41 21 69 32495.

E-mail address: edgard.gnansounou@epfl.ch (E. Gnansounou).

http://dx.doi.org/10.1016/j.apenergy.2015.10.043
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India is the fourth-largest fossil fuels consumer in the world with a demand of nearly 3.7 million barrels oil equivalent per day. Most of demand is for fuels used mainly in the transportation and industrial sectors and for kerosene and LPG in the residential and commercial sectors. India is the third-largest economy on GDP in terms of purchasing power parity basis. With its dynamic economic growth and modernization, energy demand in India will continue to rise significantly in future. With rising energy demand and increasing pollution being a main concern, Indian energy sector is exploring alternative energy sources to provide energy and to reach renewable policy goals set by the government such as 20% biofuels blending by 2017 in transport sector [7]. Several agricultural residues such as rice straw, wheat straw, sugarcane tops and leaves, bamboo etc., are available in India to produce bioethanol and to blend with gasoline. However, there are a very limited number of appropriate energy sources to produce biodiesel. Ajayebi et al. suggested that algae could be potential feed stock for biodiesel in India owing to availability of coastal line, industry and the technology [8]. However, instead of valorising algae by producing only biodiesel it may be economically promising to explore other high value co-products such as animal feed and bio-chemicals in order to utilize the full potential of algae composition [9,10].

Succinic acid is identified as one of the 30 top value products for application in industry such as 1,4-butanediol, polyurethane, plasticizers, resins, coatings, dyes & inks, pharmaceutical, food, cosmetics, solvents and lubricants and de-icing solutions [11,12]. Industrial succinic acid currently available is from fossil source; however, there is a high demand for this product due to the growing industrial application in India and China. The high demand, volatile cost and high environmental burden of petroleum based products favor introducing a bio-based succinic acid [13] that is produced by the carbohydrate fermentation using bacterial species. Biomass such as sugarcane [14], cassava [15], corn stalk [16], wheat straw and orange peel [17] were explored as feedstock for succinic acid production. Microalgae and macroalgae also show a great potential to be a substrate for succinic acid production [18–20] as algae could contain up to 15% carbohydrates depending on the strains [19].

Livestock production is a very large industry in India that contributed to nearly 4.1% of the total GDP during 2012–2013 [21] and therefore the demand for animal feed in India is huge. India is also an exporter of soybean meal and any additional protein meal would be beneficial to the export market. Algae contain up to 50% protein (dry weight basis) that could be a potential source for animal feed production. In addition it could also provide several health and marketing benefits in the livestock industry [19,22].

Considering the potential benefits that could be achieved from algae and having the facilities to grow algae, related biorefinery system could be an option for biodiesel and other value added products in India [8,23]. However, the life cycle performance of algae biorefinery systems is important to know in order to establish the environmental benefits over conventional products. In recent years, several LCA studies have been reported on biodiesel and co-products from algae and were the subject of the review paper [24]. From the product point of view, glycerol has been considered as the co-product while solid residue was considered to generate energy in [25,26,8]. In few studies, solid residue remaining after oil extraction has been considered as protein supplement [26,27]. Whereas, the solid residue has been envisaged as a substitute for fertilizer in several studies [28–31]. Sortona et al. have reported the effects of co-products on the life-cycle impacts of microalgal biodiesel considering biodiesel, animal feed and bioethanol products from algae lipid, protein and carbohydrate fractions respectively [32]. Impact results suggested that more quantity of co-products resulted in less environmental impact. However a high amount of co-products may significantly alter the impact results.

LCA of algal biorefinery has considered as products, biodiesel from lipid fraction, animal feed from protein fraction and electricity from the carbohydrate fraction [33]. It has been concluded that the economic performance of algal production systems may be improved by producing high-value compounds while improving the environment performance of biorefinery could be achieved by use of remaining fractions. On the other hand, Seth and Wangikar [38] reported the comparative LCA of ethanol, succinic acid and thermochemical products from algae. Both ethanol and succinic acid processes demand less energy input but carbon loss through fermentative respiration is 60–70%, whereas thermochemical process have smaller carbon and energy losses yielding mixture of products such as solid char, pyrolysis oil, and gaseous products. From the above literature it is clear that algal biorefinery with multiproduct could be the way forward and there is a need to explore the choice of other high value products that could incorporate in algal biorefinery based on the market demand and environmental performance [4,35,36]. Towards this context, LCA study considering biodiesel, succinic acid and protein from microalgae biorefinery has not been reported so far and the aim of this study is to assess the environmental performance of microalgal biorefinery with such product options.

From the LCA point of view, it is important to consider a relevant reference system against the system under study. While coproducts are produced from biofuel feedstock, a representative substitute product has to be selected in the reference system to include significant GHG emission or savings from byproducts and land use that could drastically influence the impact results [28,37]. In addition for electricity use in the system, the local electric mix along with renewable energy mix in the grid was taken into account to consider the overall energy mix [28]. In algal LCA studies with biofuel and co-products such as biodiesel and docosahexaenoic acid [38], ethanol and succinic acid [34], biodiesel and algae meal [33] the relevant reference systems are not defined to compare the impacts of algae biodiesel and coproducts with fossil diesel and conventional products. This study emphasizes on comparison of an algal system with reference system based on the products and co-products, along with land use change and local electricity mix. Therefore, the objective of this paper is to perform a prospective life cycle assessment related to algae biorefinery in India considering major products such as biodiesel and high value products such as protein supplement for animal feed and succinic acid. The aim is to estimate the contribution to reducing fossil energy depletion and GHG emissions.

2. Description of the process

A comparative LCA of two cases related to algae systems were performed in this paper: (1) biodiesel and protein production system, (2) biodiesel, protein and succinic acid production system. The reference system for the former study is fossil diesel and soybean protein production and for the latter it is fossil diesel, soybean protein and fossil based succinic acid production. The processes involved in the systems under study are explained in the following paragraphs.

2.1. Algal production and harvest

Microalgae could be cultivated in sea water or freshwater. Taking into account the scarcity of fresh water in India and the large scale biodiesel production capacity envisaged in this paper only seawater algae strain (Chlorella vulgaris) was considered. Microalgae absorb CO_2 for photosynthesis, therefore, source of carbon with

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