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Life cycle assessment of microalgae-based aviation fuel: Influence of lipid content with specific productivity and nitrogen nutrient effects

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HIGHLIGHTS

- Quantitative relationship between nitrogen and lipid content/specific productivity.
- Key issues for sustainable feedstock of microalgae strains in cultivation.
- The quantitative changes of LCA results under different lipid contents.
- Quantitative effects of the nitrogen nutrient on LCA results.

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ABSTRACT

The aim of this work is to compare the life cycle assessments of low-N and normal culture conditions for a balance between the lipid content and specific productivity. In order to achieve the potential contribution of lipid content to the life cycle assessment, this study established relationships between lipid content (nitrogen effect) and specific productivity based on three microalgae strains including *Chlorella*, *Isochrysis* and *Nannochloropsis*. For microalgae-based aviation fuel, the effects of the lipid content on fossil fuel consumption and greenhouse gas (GHG) emissions are similar. The fossil fuel consumption (0.32–0.68 $MJ \cdot MJ^{-1}$ MBAF) and GHG emissions (17.23–51.04 g $CO_2e \cdot MJ^{-1}$ MBAF) increase (59.70–192.22%) with the increased lipid content. The total energy input decreases (2.13–3.08 $MJ \cdot MJ^{-1}$ MBAF, 14.91–27.95%) with the increased lipid content. The LCA indicators increased (0–47.10%) with the decreased nitrogen recovery efficiency (75–50%).

1. Introduction

European Committee declared to cut greenhouse gas (GHG) emissions at least 40% by 2030. In 2009, the Air Transport Action Group (ATAG) Board developed a set of environmental targets: carbon-neutral growth starting 2020 and a 50% overall CO_2 emission reduction by 2050 (High Level Group on Aviation Research, 2011). Microalgae-based aviation fuel (MBAF) has been identified as a feasible candidate for helping to achieve this emissions target. Current research shows bio-jet fuel from microalgae can reduce life cycle greenhouse gas emissions by 76% (Fortier et al., 2014).

It is hard to achieve the information of large scale microalgae biofuel production based on the current technology, and the only way to evaluate environmental sustainability in an early phase of process design is process simulation through a life cycle assessment. Researchers discussed the choices in the process design of microalgae production systems, and the result shows that the optimization of individual parts of microalgae production systems results in better harvest concentration (result from better specific productivity), lower energy and resource usage for each part (Van Boxtel et al., 2015). Abu-Ghosh et al. realized the energy inputs analysis of the life cycle assessment (LCA) to study the oil-rich biomass production from fast-growing microalgae. Owing to the different energy consumption though cultivation and dewatering process, the result shows that the energy requirements are highly dependent on the final mass concentration (result from specific productivity) (Abu-Ghosh et al., 2015). LCA of biodiesel production from microalgae in ponds also highlighted the need for a high specific productivity, and the result showed that high specific productivity is economically viable to reduce greenhouse gas emissions (Campbell et al., 2011). However high specific productivity always associates with high nitrogen input and low lipid content. Previous research showed that fertilizer uses during culture was one of the major energy consuming activities, as a result

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of the large quantities consumption of fertilizers and the high input of fossil fuel energy in fertilizers generation process (Pragya and Pandey, 2016). Owing to the different inputs of fossil fuel energy in fertilizers generation process and emissions of nitrogen fertilizers, results showed that variety in nitrogen fertilizer also strongly effects the climate change (Collet et al., 2014).

There are two critical characteristics for microalgae feedstock in microalgae-based aviation fuel: lipid content (generally given as a weight percent of total biomass) and specific productivity (generally given in $mg \cdot L^{-1} \cdot d^{-1}$) (Stratton et al., 2010). A sensitivity analysis was performed to determine key parameters affecting LCA results by (Frank et al., 2011a). The result also showed that lipid content and specific productivity are both chosen as key parameters.

Although a large number of microalgae strains have been detected, only a few of them can be practically used for commercial purposes. The selection of available microalgae strains is an important step for achieving aviation biofuel production. The ideal algal strain for biofuel production should have high lipid productivity, high CO_2 absorbing capacity, and high specific productivity with less nutrient requirement (Brennan and Owende, 2010). Microalgae strains have a large range of lipid content (Procházková et al., 2014), which can be modified by optimizing the growth determining factors including the control of nitrogen, light intensity, temperature, CO_2 concentration and harvesting procedure. However, lipid accumulation refers to increased concentration of lipids within the microalgae cells without consideration of the overall biomass production, and is just opposite to the specific productivity (Brennan and Owende, 2010).

The main objective of this study is to examine the effect of lipid content (nitrogen effect) on total energy input, fossil fuel consumption and GHG emissions and to decide whether high or low lipid content is desirable under the specific cultivation conditions. As the nitrogen deficiency is beneficial for high lipid microalgae but with a lower specific productivity, comparison of low-N and normal culture conditions have been assessed by LCA for balance between the lipid content and specific productivity. Moreover, the relationships have been established between lipid content (nitrogen effect) and the specific productivity as well as total nitrogen consumption based on three different microalgae strains including *Chlorella*, *Isochrysis* and *Nannochloropsis*.

2. Materials and methods

2.1. System boundary

The GREET 1_2014 (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) and APD_v1.1 (algae process description) models (Argonne National Laboratory, 2014) are used to conduct the LCA. Detailed descriptions of the GREET 1_2014 and APD_v1.1 models can been found in (Elgowainy et al., 2012; Frank et al., 2011a, 2011b). The database based on GREET 1_2014 has been modified according to the original Chinese government data release (Zhao et al., 2015). Fig. 1 indicates the system boundary of microalgae-based aviation fuel technology process in this research. The system boundary doesn't consider the contribution of infrastructure and aircraft. The life cycle of MBAF begins with microalgae cultivation accompanying with CO_2 transportation and fertilizer supply and ends with aviation fuel combustion in the aircraft (Elgowainy et al., 2012; Frank et al., 2011a). Key assumption parameters are listed in Tables S1 (Supplementary Information).

2.2. Case study

2.2.1. Microalgae growth inventory data

This paper pays attention to lipid content and total nitrogen consumption for three microalgae strains. There are several factors influencing algal lipid content and specific productivity, such as light (quality and quantity), temperature, nutrient input, O_2, CO_2, pH, salinity, harvest frequency, etc. Among these factors, the total nitrogen consumption present in cultivation is considered to be the most significant one and has a direct influence on algal lipid content and specific productivity (Xin et al., 2010). Moreover, the nitrogen nutrient could lead to N_2O emission in production and utilization, a potent greenhouse gas with global warming potential 298 times than that of CO_2 for a 100-year horizon (Alcántara et al., 2015). The GHG emissions calculation combines carbon dioxide, methane, and nitrous oxide with their global warming potentials (1, 25, and 298, respectively, based on a 100-year horizon) (Elgowainy et al., 2012). The results of other researchers showed that N_2O emissions can have an important impact on the overall GHGs balance of biofuels (Bauer et al., 2016). Therefore, for better understanding the influence of nitrogen nutrient on lipid content and specific productivity, total nitrogen consumption and different nitrogen recovery efficiencies have been assessed by the contribution on the life cycle greenhouse gas emissions and total energy input.

There are more than 200,000 species of microalgae exist (Norton et al., 1996), and the types of microalgae available at fresh water and marine water and their possible ranges of lipid contents are shown by Alam et al. (2012). Most of heterotrophic microalgae strains have the characteristics of high lipid including *Botryococcus* sp. (25–75%), *Scenedesmus obliquus* (11–55%), *Chlorella* sp. (10–48%) in fresh water and *Dunaliella* sp. (18–67%), *Dunaliella tertiolecta* (18–71%), *Phaeodactylum tricornutum* (18–57%), *Neochloris oleoabundans* (40–65%) in marine water (Alam et al., 2012). The autotrophic microalgae species, *Chlorella* (14–63%), *Nannochloropsis* (21–59%), and *Isochrysis* (14–45%), which listed in Tables S2 (Supplementary Information), have advantage in high lipid content and scale cultivation possibilities, and have been chosen as the feedstock of the LCA model in this study.

The lipid contents of the three microalgae strains under different total nitrogen consumption, are listed in Table S3 (Supplementary Information) with specific productivity and harvest concentration of microalgae strains. The total nitrogen consumption in Table S3 (Supplementary Information) doesn't consider the nitrogen recovery efficiency, the added new nitrogen used in the life cycle will be shown in next section. As the microalgae growth process is dynamic, nitrogen in culture drops dramatically at the early growth phase. These cells may grew with available N until the culture is (almost) depleted of nitrogen. Then they will decrease the growth rate and start accumulating lipid. The final lipid content of the microalgae will signify the ratio of the total nitrogen consumption as well as the time available after switching to lipid production. Table S3 (Supplementary Information) also shows the growth cycle time used in this model. The cultures were left to grow until the late exponential phase/early stationary phase was reached.

Total nitrogen consumption (TN, mg N) is the total nitrogen input minus the residue value per liter in a growth cycle. The protein content is calculated by the TN (5% lost (Frank et al., 2011a)) multiplied by a factor of 6.25/harvest concentration (Xia et al., 2016) when there is no protein content data in the references. In this model, the sum of lipid, protein and carbohydrate content is hypothesized to be 100%. The carbohydrate content is obtained by 100% minus the sum of lipid and protein content (ash free dry