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Life cycle cost of biodiesel production from microalgae in Thailand

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ABSTRACT

Biofuels derived from microalgae are currently gaining attention as alternative fuels, especially for substituting biodiesel. Microalgae can be grown either in open pond systems or in closed photobioreactors. However, the systems require a high initial capital investment for construction of pond and photobioreactor systems. This study aims to evaluate the financial feasibility of two types of large scale microalgae-based biodiesel production assumed to be located in the northern region of Thailand. Four algae-to-biofuels process scenarios were examined: base cases of raceway ponds and photobioreactors including only biodiesel production; and alternative cases for both, including extraction of high value added products, omega-3 fatty acids, in addition to biodiesel. The basis of biodiesel production was 720,000 L per year operated for 15 years. For the base case, the biodiesel production costs for algae produced from raceway ponds and photobioreactors were 68 and 224 Thai Baht/L, respectively, while for the alternative case, they were 191 and 450 Thai Baht/L, respectively. Even though the omega-3 fatty acid production gained higher revenue, the capital cost and operating cost would need to be reduced at least 50% to make the systems profitable. Several improvement options and possible government incentives to achieve this are presented.

Introduction

The rising energy demand in many rapidly developing countries around the world is beginning to create intense competition for the world's dwindling petroleum reserves. The world oil markets are expected to continue to tighten, leading to higher oil prices (EIA, 2011). The gross domestic product in Thailand has continuously increased along with a substantial increase in energy consumption. Thailand is obligated to import a large amount of crude oil to meet domestic demand. In 2012, net crude oil accounted for 3655 million L costing about 64,447 million Thai Baht (1 USD = 32 THB - Thai Baht in 2013) (EPPO, 2013). The transportation sector relies largely on imported fossil fuels and this has raised concerns about economic and national security. There is an increasing interest in alternative, renewable energy sources. At present, biomass-based liquid transportation fuels such as biodiesel and bioethanol, are alternatives to substitute petroleum-based fuels. However, the priority use of food crops for human and animal nutrition can create a competition of biofuel with food production, land use and has a potential for increasing food prices (Gheewala et al., 2013).

Microalgae are presented as an alternative renewable fuel feedstock that could avoid food versus fuel conflict. They can be grown on non-arable lands including saline soil lands or even desert lands not being used to produce food (FAO, 2009; IEA Bioenergy, 2010). Thus, they would be not competing for arable land that is needed for production of food crops and animal feed production; they also seem to be an attractive way to produce biofuels due to their ability to accumulate lipids when grown under certain specific conditions, such as nutrient limitation. Some species are extremely high in lipid content (microalgae may accumulate up to 60% lipids under nitrogen-limited conditions) with potential for an annual production of 20–40 tons lipid per hectare e.g. *Nannochloropsis oculata* and *Chlorella vulgaris* (Oh-Hama and Miyachi, 1988).

Microalgae can be grown either in an open pond or in a closed photobioreactor system. Open ponds are relatively low-cost to construct for large-scale algal biomass production. However they cannot prevent the contamination from invading microorganisms. Photobioreactors are designed to overcome these problems. Unlike open ponds, photobioreactors permit culture of single-species of microalgae for prolonged durations with lower risk of contamination, and also achieve a higher algal cell density due to higher surface area-to-volume ratio. However, photobioreactor systems have a very high initial capital investment for equipment.

Currently there are private companies in Thailand actively producing commercial nutrition food extracted from microalgae. However, there are no commercial scale facilities for algae derived biodiesel in the country yet. One of the largest problems facing the biofuel business is how to attain high productivity while reducing capital and operating costs. Numerous studies have been published on the economic feasibility of commercial algae production particularly alternative harvesting and extraction techniques (Chisti, 2008; Molina Grima et al., 2003;

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Olaizola, 2003; Tredici, 2004). However, there are still relatively few studies focused on the economics of the high value co-products to make a profit or return on investment competitive with fossil based fuels. Algal biomass can provide many valuable co-products such as algal meal, omega-3 fatty acids, organic pigments and advanced compounds which might enhance the profitability of the algal biofuels (Subhadra, 2010).

This study aims to evaluate the economic feasibility of biodiesel production derived from microalgal oil as a base product and high-value chemicals as the alternative co-products in both open ponds and closed photobioreactors in Thailand.

Materials and methods

The study examines financial feasibility of commercial algal plants. The 15-year net present value is used as an indicator of the profitability of different production scenarios. Based on high growth rates and lipid content, *C. vulgaris* is chosen as the representative species for algal production (Brennan and Owende, 2010). The study site is located in Chiang Mai province in the northern region of Thailand as there are already several existing commercial algal plants. The facility is assumed to operate 330 days per year with suitable environmental conditions ensuring high productivity (temperatures between 20 and 30 °C and optimal solar irradiance) (Table 1).

Algal growth assumptions

The study provides a 15 years' analysis based on the service life time of equipment. Assumptions on the algal growth to meet a target of 720,000 L/year for biodiesel production were derived from literature adapted to the conditions for Thailand (Amer et al., 2011; Davis et al., 2011 and Sun et al., 2011). To provide a basis of comparison, this study analyzed an open pond and photobioreactor algae farm. The production methods in Table 1 are tuned to optimal combinations of biomass productivity and concentration for large scale raceway pond and photobioreactors, achieving algal cell densities of 0.5 g/L and 4 g/L, respectively (Chisti, 2007; Molina Grima et al., 2003). It can be seen that photobioreactors provide much higher areal productivity compared to raceway ponds.

The carbon supply is provided by flue gas assumed to be obtained from a nearby natural gas-based power plant; this is much better than capture of atmospheric CO_2 as the CO_2 concentration in the flue gas can be as high as 20% facilitating algal growth (Bilanovic et al., 2009). The gas is injected directly into the photobioreactors but transferred via sumps for the open ponds; the latter have a water depth of 20 cm and are mixed using paddle wheels (Shen et al., 2009). The design for open ponds is based on Darzins et al. (2010) with a water evaporation rate of 0.3 cm/day. The photobioreactors consist of tubes in parallel rows, each tube having a dimension of 8 cm ID × 80 m length. Between the tubes is a degassing station used to remove dissolved oxygen which produces photooxidative damage to algal cells and to provide circulation. The photobioreactors are cooled by spraying water on the tube surface via a sprinkler system. The design for photobioreactor system was based on the study by Lundquist et al. (2010). The growth medium required for producing microalgal biomass comprises inorganic and essential elements including nitrogen (N), phosphorus (P) and iron (Fe). The requirements for CO_2 and nutrients were based on stoichiometry assuming an algal composition of $C_{106}H_{181}O_{45}N_{15}P$ (Clarens et al., 2010). The production facilities are continuously harvested at a rate equal to the growth rate. The algal slurry is sent to a simple settling tank where autoflocculation of algal cells is performed using aluminium sulfate followed by centrifugation. Homogenization is used to break open the cells and the algal lipids extracted using hexane to achieve 90% extraction efficiency. After oil extraction, anaerobic digestion is used to generate methane (CH_4) from the residual biomass (Fig. 1), which is then combusted and sent to a boiler to provide process heat. Any excess would be sent to the natural gas-fired power station fired to generate electricity as power credit. Therefore, allocation by substitution was employed, e.g., heat from the combustion of a by-product could replace heat that would have been supplied from the common system, using natural gas. Additionally, emerging challenges of using microalgal residue as aquaculture feed have been considered by comparing anaerobic digestion in term of annual profitability. The process used to refine the oil and produce biodiesel is assumed to be the same as that used for the production of biodiesel from palm oil in Thailand. The refinery plant is assumed to be located in Chiang Mai province, where the algal oil is transported for biodiesel production over a distance of 32 km via a 22.5 ton capacity heavy truck.

Four algae-to-biofuel process scenarios were examined as follows: (i) a base case of pond system (without omega-3 fatty acid production), (ii) an alternative case of pond system (with omega-3 fatty acid production), (iii) a base case of photobioreactor system (without omega-3 fatty acid production), and (iv) an alternative case of photobioreactor system (with omega-3 fatty acid production). A biomass processing capacity of 2812 tons per year was considered for producing 720,000 L algal biodiesel per year which is used as the basis of this study. The base case of two systems is projected to produce 720,000 L per year of biodiesel as the primary product along with glycerin at 62.2 tons per year as the co-product. The alternative case is projected to produce 432,053 L per year of biodiesel plus omega-3 fatty acids and glycerin at 239.02 and 37.3 tons per year, respectively as the co-products.

Economic assumptions

For this study, the capital and operating costs are obtained from secondary sources. The capital costs are taken from an algal culture facility in the United States (Benemann and Oswald, 1996; Davis et al., 2011; Richardson et al., 2012) and the operating costs from Stephenson et al. (2010) and Lardon et al. (2009). The latter are also used as input data for mass and energy balances. All costs in previous literature are converted to Thai currency and updated to 2012 by using the projections of annual inflation rates from the Bank of Thailand.

The financial assumptions (from BOT, 2012; Davis et al., 2011 and Richardson et al., 2012) used in this study are summarized below:

- Maintenance cost is 2% of capital cost
- Interest rate is 7.31%
- Contingency is 30%
- Price index for year 2012
- Depreciation rate is 6.7% per year
- Tax rate is 20%
- Capital investment loan duration is 10 years.

Processing assumptions for base case and alternative case

Chlorella has a large amount of polyunsaturated fatty acids (PUFAs), including omega-3 fatty acids. Nutritionally, eicosapentaenoic acid (EPA, 20:5) and docosahexaenoic acid (DHA, 22:6) are the most

Table 1
Baseline algal growth assumptions (Davis et al., 2011).

Algal growth assumption	Open pond	Photobioreactor
Areal productivity (g dried cell weight/cm^2/day)	25	40
Triacylglyceride content (% dried weight)	25	25
Target cell density (g dried cell weight/L)	0.5	4
Operating day (days/year)	330	330
Scale (L/year algal oil)	813,600	813,600