Transportation Fuels from Algae: Addressing Bangkok's Petroleum Needs

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Abstract: The purpose of this study is to assess the practicality of algal biofuel production and consumption in Bangkok, Thailand based on the environmental impacts of and ability to offset the petroleum equivalents. A life cycle assessment was conducted to determine the environmental impacts of algal biofuels - biodiesel, ethanol, and compressed biomethane - replacing low-sulfur diesel, standard gasoline, and compressed natural gas (CNG), respectively. Three scenarios with two algae strains were compared for the production of biofuels using net energy ratio (NER) and vehicle kilometers traveled (VKT). For *B. braunii,* the biodiesel and compressed biomethane producing scenario had the highest VKT of 1,220,000 and an NER of 1.26 using a functional unit of 1 hectare of algal ponds. For the "generic" strain, biodiesel and compressed biomethane produced the highest VKT of 1,200,000 with a NER of 1.25. For *B. braunii* and generic strains, the production of only compressed biomethane showed NERs of 1.45 and 1.50 respectively, but VKTs of 936,000 and 976,000. Environmental impacts from algal biofuels are higher than petroleum fuels in all categories considered. Available land area would yield enough algal biofuels to replace <1% of petroleum fuel usage. While there is a positive energy ratio associated with the production of algal fuels, Bangkok's planners need to consider the limited land availability and the higher pollution from algal fuels before committing to an algal biofuel program.

Keywords: Algae, biofuels, *B. braunii*, life cycle assessment, petroleum, renewable.

1. Introduction

As the world's supplies of fossil fuels diminish and greenhouse gas emissions increase, nations across the world are working to provide sources of alternative energy. In Thailand, nearly all of the energy used for transportation comes from petroleum products. Such little fuel diversification leaves the country vulnerable to possible supply constraints and price increases in the future as well as endangering future generations by the unrestricted burning of fossil fuels [1].

To counter these effects, Thailand aims to increase its production and consumption of renewable fuels and this study will assess the feasibility of biofuels derived from algae. Current Thai policy focuses mainly on biodiesel and ethanol production. This study will additionally look at the production and use of compressed biomethane to meet the increasing demands for natural gas [2]. With regard to the newly implemented biodiesel and ethanol policies, Thailand needs to expand its feedstock production of biodiesel and ethanol before biofuels produced from algae could be a potential source. Most biodiesel in Thailand is made from palm oil, while ethanol comes from sugarcane molasses and cassava. Attempts to increase the production of these feedstocks have been challenged by competition over Thailand's limited supply of suitable farmland [3].

In this respect, biofuels from algae have great promise. Algae could prove to be superior to terrestrial crops as a fuel source due to its higher photosynthetic capabilities, higher lipid and starch yields, higher growth rate, and lower land use requirements than conventional biofuel feedstocks [4]. Algae can be grown in freshwater, saltwater, or wastewater and therefore do not require arable land or potable water to grow. Cultivating algae in wastewater can reduce the need for fertilizer production and can provide the added benefit of wastewater treatment if the algae are grown using the nutrients from wastewater treatment plants [5].

Thailand has an ideal climate for growing algae on a large scale. However, further research is needed to demonstrate the feasibility of algal biofuel production in Thailand. As part of the feasibility study, production of various biofuels was examined as well as the environmental impacts of each option evaluated in a life-cycle assessment format.

2. Methods

2.1 Goal and Scope

This study aims to (1) select the best strategy for algal transportation fuel production in Bangkok, Thailand, based on vehicle kilometers traveled (VKT), the distance a standard compact passenger vehicle travels from the algal biofuel produced, and net energy ratio (NER), the ratio of energy returned to energy invested; (2) compare the algal biofuels produced from the selected scenario to petroleum fuel equivalents with respect to the life cycle environmental impact potentials, including global warming, acidification, photochemical ozone creation and eutrophication potentials, accounting for all the pollution created as per the CML LCIA method; (3) gauge the feasibility of biofuels offsetting Bangkok's petroleum needs given the available land area for algae cultivation in Bangkok.

This study focuses on the production of three algal biofuels: (a) biodiesel produced by transesterification to be blended into a 95% diesel, 5% biodiesel blend (B5) and combusted in a conventional diesel engine, (b) ethanol produced by yeast fermentation to be blended into a 90% gasoline, 10% ethanol blend (E10) and combusted in a conventional gasoline engine, and (c) biomethane produced by anaerobic digestion that is compressed and used for combustion in dedicated compressed natural gas (CNG) vehicles. Since commercial scale production of algal biofuel is not yet available in Thailand, production data was found in academic literature and adapted to reflect the growth models. Values are reported to last significant digit considering uncertainty. Uncertainty and all supporting calculations are shown fully in the supporting information.

2.2 System Boundaries

A "well-to-wheel" life cycle assessment is performed for biodiesel, ethanol, and biomethane produced from algae (Fig. 1). The steps included are: cultivation of algae, harvesting, conversion of algae biomass to biofuels, and the combustion of the produced biofuels in a passenger vehicle. The life cycle inventory analysis in this study quantifies the life cycle energy usage from scenarios of various algal biofuel production, described in Section 3.2. The life cycle air emissions and environmental impacts of algal biofuels are calculated and compared to life cycle environmental impacts from conventional transportation fuels, including diesel, gasoline, and CNG. This study does not account for the energy and resources necessary to build the infrastructure to grow algae, harvest biomass, or produce algal biofuels due to the long lifetime of the required infrastructure [6].

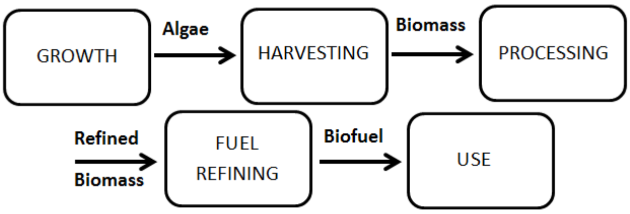

Figure 1. "Well-to-wheel" Life Cycle for Algal Biofuel Production.

2.3 Unit of Analysis

The functional unit of the study is to move a passenger vehicle 1,000 km based on standardized driving behavior in city traffic measured in Bangkok, Thailand [7]. The purpose of this study is to assess the feasibility of replacing conventional petroleum fuels with algal biofuel substitutes. Thus all available algae is converted into fuel where possible and intermediary byproducts are not considered where a biofuel alternative is possible.

The reference flow for the functional unit is the amount of each fuel type necessary to move a passenger vehicle 1,000 km based on standardized driving behavior in city traffic measured in Bangkok, Thailand [7]. Reference flows were calculated using the gasoline equivalent of each fuel type, normalizing for engine efficiency and energy density of fuels and are shown in Table 1.

Table 1. Reference Flows for Each Fuel Type.

Fuel	Reference Flow (L per 1000 km)
Gasoline	84.8
Diesel	57.1
Compressed natural gas	225
Compressed algal biomethane (25 mPa at 21°C)	230
E10	86.1
B5	57.3

As the final portion of the study is designed to determine the best fuel type to produce given the same input of algae, net energy ratio and vehicle kilometers traveled were used to compare fuel types. Net energy ratio (NER) is reported as total fuel energy output divided by the primary energy input. Vehicle kilometers traveled (VKT) are the total number of kilometers a passenger vehicle can travel given the combustion of all the fuel produced in a given scenario. Examining NER and VKT allows for the fair comparison between fuels with different energy inputs of production and between fuels with different calorific contents and burning characteristics. VKT are calculated using the reference flows from Table 1.

Gasoline engines are assumed to be 30% efficient while diesel and CNG engines are assumed to be 40% [8]. The energy densities used are 29.7 MJ/L for gasoline, 36.1 MJ/L for diesel, 9.18 MJ/L for CNG, and 8.96 MJ/L for compressed biomethane gas (CBG) [9]. E10 fuel usage is assumed to increase 1.5% by volume from 100% gasoline combustion, and B5 is assumed to be a 0.4% increase by volume from 100% diesel combustion [10-11]. These reference flows are summarized in Table 1 below.

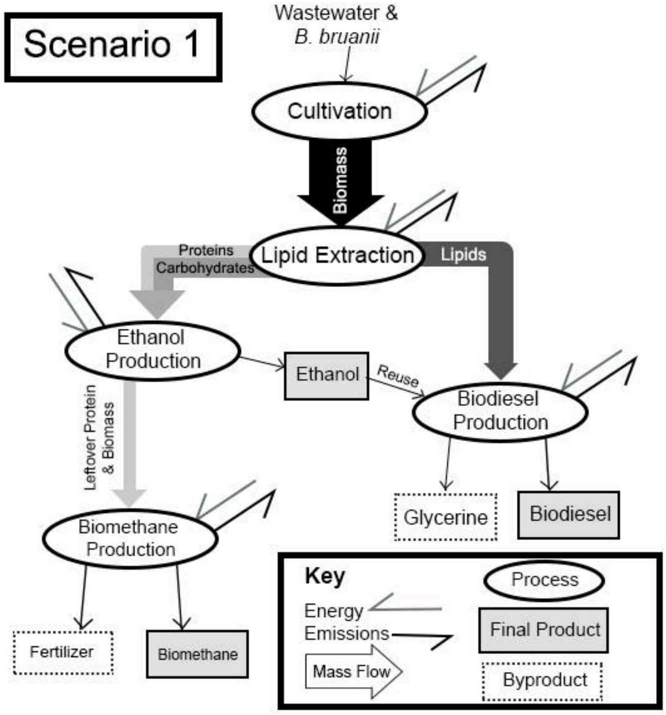

Figure 2. Scenario 1 Process Diagram. Scenarios 2 and 3 follow similar processes, but Scenario 2 excludes "Ethanol Production," and Scenario 3 excludes "Lipid Extraction," "Biodiesel Production," and "Ethanol Production."

3. Life Cycle Inventory

3.1 System Design

The assumed pond design is consistent with industrial standards: 10 m wide × 100 m long × 0.3 m deep, oval-shaped pond built with concrete blocks, on a 10-cm thick sole. A PVC liner covers the concrete to decrease roughness and to avoid biomass attachment. Each pond spans a growth area of 0.1 hectare (ha). Thus, a 1 ha growth area accommodates 10 ponds. The algae grown in one ha of ponds is the unit of measurement used for many process flows throughout the present study. Algae is grown in Bangkok wastewater having a nutrient content of 184 mg/L nitrogen and 18.6 mg/L phosphorus [12]. The wastewater is provided from a nearby municipal wastewater treatment plant, thereby limiting algae cultivation to locations adjacent to wastewater treatment plants for the purposes of this study.

3.2 Biofuel Production Scenarios

Three fuel production combinations are modeled in the present study for the purpose of finding the scenario with a positive net energy ratio (NER) and the maximum usable energy output in the form of vehicle kilometers traveled (VKT) for Bangkok, Thailand.

- Scenario 1: Lipids are extracted from the algae biomass and used to make biodiesel. The carbohydrates are then extracted from the remaining biomass and put towards ethanol production. A portion of the ethanol produced in this process is recycled for use in biodiesel production. The final biomass content, containing mostly proteins, is converted into biomethane via anaerobic digestion.

- Scenario 2: Lipids are extracted from the biomass and used to make biodiesel. The remaining biomass, consisting of mostly carbohydrates and proteins, is converted into biomethane via anaerobic digestion.
- Scenario 3: All of the biomass is converted to biomethane via anaerobic digestion.

3.3 Estimating Algae Growth and Composition

Two strains were selected for this study. *Botryococcus braunii* was considered as the ideal case for biodiesel production due to its high growth rate and high lipid content. The other strain was an average of several algae strains, representing a potential "generic" strain likely found in Bangkok. The biomass productivities and compositions of both strains are determined in the following sections.

3.3.1 *B. braunii*

The present study is based on an Indian strain, *B. braunii* AP103, cultured in CHU 13 medium and grown in a pilot scale raceway pond in Tamil Nadu, India [13]. CHU 13 medium is a culture medium including essential minerals and trace elements required for growth of certain algal species, including *B. braunii*. One of the most important aspects of *B. braunii* that sets it apart from other fast-growing, lipid-producing strains is its high hydrocarbon content. Hydrocarbons can be extracted from the algae with lipids and used to produce biodiesel. The present study considers the effects of using wastewater as a medium on the growth of algae. When the nitrogen content of wastewater is adjusted to the Bangkok wastewater level, the growth rate of algae increased by 2.9%, hydrocarbon content increased by 47%, and lipid content increased by 31.5% compared to algae grown without the addition of nutrients [14-15]. *B. braunii* is modeled as grown in 2% carbon dioxide. The addition of 2% CO_2 leads to a 22% increase in total biomass, 48% increase of hydrocarbons, and 5.1% increase in lipid content compared to the control [16-17]. After accounting for these increases, the final biomass content of *B. braunii* is 0.15 g/L-d, consisting of 39% lipids and hydrocarbons, 33% carbohydrates, and 18% proteins. Final biomass productivities and compositions of *B. braunii* are shown in Table 2.

Table 2. Final Biomass Productivities and Compositions for *B. braunii* and Generic Strain.

Final Algae Content	*B. braunii (Mg/ha-year)*	Generic strain *(Mg/ha-year)*
Biomass	174	195
Lipid & Hydrocarbon	66	50
Carbohydrate	56	45
Protein	31	86

3.3.2 Generic strain

The biomass productivity and composition of the generic strain were calculated by averaging values of 14 algae strains from Wenguang et al. [17] and 17 algae strains from Jasvinder & Sai [18]. In these studies, the algae was cultivated in wastewater under otherwise natural growth conditions. The algae strains are, therefore, assumed to exhibit natural growth, comparable to that of an average strain grown in Bangkok without intensive cultivation requirements. Because the generic strain is assumed to be grown under natural conditions, carbon dioxide is not added. For the averaged generic strain, the resultant biomass productivity is 0.21 g/L-d, composed of 28% lipids, 23% carbohydrates, and 44% protein. The generic strain's final productivity and composition are shown in Table 2.

3.4 Cultivation

The pond has several energy requirements related to the water that must be pumped to and from the pond and stirred by paddle wheels, and the 2% CO2 that is assumed to be compressed at a nearby power plant and delivered to the algae pond. All energy values for cultivation, harvesting, and biofuel conversion as well as credits from co-products are summarized in Table 3.

3.5 Harvesting

Algae biomass is harvested to achieve a low water content using flocculation from alum followed by gravity thickening. In flocculation, the addition of alum causes algae to clump by neutralizing the electrode double layer surrounding them [20]. Once clumped, the algae will settle to the bottom and be directed to a collection point via gravity thickening. The final algal concentration is approximately 140 g/L, which is assumed to be a suitable concentration for subsequent steps without the need of further dewatering [6].

3.6 Biofuel Conversion

3.6.1 Biodiesel

The biodiesel production process consists of homogenization, thermal pretreatment, lipid extraction, transesterification, and blending. Homogenization is required to break the algae cell walls to allow hexane to extract the lipids [6]. Before lipid extraction, *B. braunii* must undergo thermal pretreatment to fully extract the available hydrocarbons. Thermal pretreatment involves heating the algae biomass up to 60°C for 10 minutes [21]. Lipids and hydrocarbons are extracted using hexane and are refined into biodiesel by the process of transesterification. The final yield of biodiesel can be calculated using the total lipid yield and considering 4% loss in homogenization, 15-20% loss through lipid extraction with hexane, and 3.6% loss of lipids entering the transesterification reaction [6]. The biodiesel is then transported to refineries in Rayong, Thailand, where it is mixed with 95% diesel by volume and transported back to Bangkok for distribution.

3.6.2 Ethanol

Carbohydrates from algae can be converted into ethanol via yeast fermentation. Lipid extraction prior to ethanol conversion is not necessary but is ideal, as demonstrated in a study by Harun et al. [22] in which lipid-extracted algae yielded 60% higher ethanol concentrations than dried, intact algae. The ethanol conversion process follows lipid extraction for biodiesel production and consists of the following steps: saccharification, fermentation, distillation, dehydration, and blending. Saccharification, also known as hydrolysis, converts the complex carbohydrates into simpler sugars that can be fermented by yeast into a dilute ethanol solution (10-15% ethanol).This solution is subjected to distillation in which water and impurities are removed to produce 95% concentrated, liquid ethanol. Dehyrdation removes more water, so that the final product is 99.5% ethanol. Finally, the concentrated ethanol is transported to oil refineries in Rayong, Thailand, where it is blended to the desired ratio. This report examines ethanol in the form of E10, a blend that is 10% ethanol, 90% gasoline by volume.

The theoretical ethanol yield can be calculated based on the chemical equation relating the fermentation of hexose to the production of ethanol and CO_2: $C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2$. It is assumed that 75% of the carbohydrate content can be hydrolyzed into fermentable hexose and that the obtained ethanol yield is 80% of the theoretical yield [23].

3.6.3 Biomethane

Algal biomass goes through multiple steps to be processed into biogas that is upgraded into 96% biomethane gas and then compressed to be utilized in vehicles as a transportation fuel. Algal biomass is loaded into an anaerobic digester where microorganisms break down the biomass to produce a biogas that is 70% biomethane and 30% CO_2. The biogas is then bubbled through pressurized water, where the carbon dioxide and particles are separated from the methane, leaving a 96% concentration of biomethane gas [24]. The biomethane is compressed at the pump from a pressure of 0.1 mPa to a pressure of 25 mPa. The theoretical biomethane yield is modeled from the relation between biomethane yield and respective carbohydrate, protein, and lipid contents as reported in Angelidaki and Sanders [25]. Based on findings by Ras et al. [26], it is assumed that obtained methane yield is 60% of theoretical methane yield.

3.7 Co-products

3.7.1 Treated wastewater

The majority of the wastewater in Bangkok goes through secondary treatment. However, without a subsequent tertiary treatment, the wastewater is not clean enough to reach government standards in terms of pH, total nitrogen, total phosphorus, suspended solids, and chemical oxygen demand. Sreesai and Pakpain [12] show that growing algae in wastewater as a tertiary treatment can significantly reduce the amount of total nitrogen and total phosphorous in the wastewater effluent, helping it to reach the standards outlined by the Thai government. Submerged membrane bioreactors coupled with activated sludge provide similar treatment results as algal tertiary treatment, in terms of percent reduced total nitrogen and chemical oxygen demand [27]. Algae growth is assumed to replace this method of tertiary treatment. Visvanathan et al. [27] reports the energy consumption of this tertiary treatment method to be 0.0252 MJ/m^3. The volume of water treated in the ponds is calculated to be 91,250 m^3/ha-year, based on the system design of 3,000 m^3/ ha and 12 day growth cycles. Under this assumption, tertiary treatment by algae would offset a wastewater treatment energy demand of 2,300 MJ/ha-year.

3.7.2 Glycerol

Glycerol is obtained as a by-product of biodiesel production. The yield of glycerol is 213 kg per Mg of biodiesel [28]. Based on current market prices, the glycerol co-product would represent 7.74% of the total economic potential if the products were sold at market prices [29]. Based on glycerol's properties and uses, economic allocation seems the most appropriate way to allocate the environmental burdens between co-products and is used for the remainder of the study.

3.7.3 Fertilizer

Following biomethane production, a digestate high in nitrogen, phosphorus, and potassium is left, which can be sold as fertilizer. This digestate is assumed to replace fertilizer produced in Thailand, which requires energy inputs of 35.3 MJ/kg N, 36.2 MJ/kg P, and 11.2 MJ/kg K and the final energy offset per m^3 of digestate production is 186.37 MJ/ m^3 [30]. Transportation of digestate fertilizer is assumed to be comparable to transportation of inorganic fertilizers as both will be produced and consumed within Thailand. Therefore, transportation of fuels is considered equal and is not counted in energy offsets. These energy inputs are shown below in Table 3, followed by a summary of fuel production per scenario in Table 4.

Table 3. Summary of energy inputs for biofuel production.

Process	Electricity output	Unit	Sources
Cultivation			
Pumping	40,800	MJ/ha-yr	[6]
Stirring	1,170	MJ/ha-yr	[6]
CO_2 aeration	38,700	MJ/ha-yr	[6]
Harvesting			
Alum upstream production	78,000	MJ/ha-yr	[20]
Gravity thickening	11.0	MJ/ha-yr	[6]
Biodiesel			
Homogenization	825	MJ/Mg biomass	[6]
Thermal pretreatment	115	MJ/Mg algae	[31]
Lipid extraction	123	MJ/Mg biomass	[6, 21]
Hexane upstream production	880	MJ/Mg biomass	[6]
Methanol production	1.11	MJ/L biodiesel	[28]
Steam production	0.561	MJ/L biodiesel	[28]
Electricity production	0.111	MJ/L biodiesel	[28]
Sodium methoxide production	0.296	MJ/L biodiesel	[28]
Sodium hydroxide production	0.0143	MJ/L biodiesel	[28]
Hydrogen chloride production	0.0143	MJ/L biodiesel	[28]
Transport for blending	0.330	MJ/L biodiesel	[28]
Ethanol			
Saccharification	0.410		[32]
Fermentation	0.990		[32]
Distillation	14.2		[32]
Membrane refining	0.690		[32]
Transport for blending	0.290		[28]
Biomethane			
Mixing	389		[24]
Centrifugation	90.7		[24]
Internal biogas used	2,450		[24]
Purification	1.10		[24]
Compression	0.453		[33]
Credits			
Wastewater treatment	2,300		[27]
Fertilizer production	186		[6,30]
Glycerol production*			[28]

*Glycerol production is assigned 7.4% of the energy inputs of biodiesel production based on economic allocation.
Sources: [11] Kraatz, 2008

4. Results

4.1 Scenario Results

The fuel production (Table 4), NER, energy output, and VKT for each scenario are compared in Table 5 below. Energy usage was calculated by scenario rather than by output fuel when multiple fuels were produced. The inputs were left undivided rather than allocated by fuel as the three scenarios represent all possible routes for full biomass usage. Any other scenario, for example, one that produced only ethanol or biodiesel, would not use all available biomass. As this study focuses on the production of transportation fuels, any other scenario is impractical and is not considered in this study.

4.1.1 *B. braunii*

Scenario 1 shows the lowest NER value. Ethanol production yields negative energy, requiring a primary energy input of 840,000 MJ for production and supplying only 295,000 MJ of fuel energy. Scenario 3 shows the highest NER, representing the greatest process efficiency; however the total yield of energy is lower than for Scenario 2.

4.1.2 Generic strain results

Consistent with *B. braunii*, Scenario 1 again shows the lowest NER value. Ethanol production yields less energy than needed for production, requiring a primary energy input of 670,000(+/-13,304) MJ for the conversion process, and yielding 232,000 MJ of fuel energy. Similar to *B. braunii*, Scenario 3 returns the highest NER, but lower net energy output compared to Scenario 2. All NER values in Scenarios 1 and 3 obtained with the generic strain are higher than those obtained with *B. braunii*.

B. braunii shows a higher VKT in all scenarios excluding Scenario 3. It should be noted that NER values do not show large differences when comparing between strains. Scenario 3 for both strains showed the lowest energy production of all scenarios. This was due to relatively lower biogas conversion of lipids as compared to biodiesel production. Found in Table 5 below are values for all biofuel scenarios' energy inputs and outputs, NER, and VKT.

Table 4. Fuel Production per Scenario.

Scenario	Strain	Biomethane (L/ha-yr)	Biodiesel (L/ha-yr)	Ethanol (L/ha-yr)
1	*B. braunii*	23,600	57,800	13,800
2		66,800	57,800	--
3		215,000	--	--
1	Generic	78,200	43,900	10,900
2		112,000	43,900	--
3		225,000	--	--

4.2 Comparison to Conventional Fuels

The most promising scenario for each strain was selected to compare to conventional fuels. As the purpose of this study is to assess petroleum offset, the scenario which resulted in the highest VKT with a positive NER (greater than 1.00) was chosen. For both strains, this is Scenario 2.

The algal biofuels produced in Scenario 2, biodiesel and compressed biomethane gas (CBG), were compared to diesel and natural gas based on environmental impacts. Because the algal biodiesel is blended with diesel, the combustion emissions of biodiesel are mostly attributed to diesel combustion. With the addition of 95% diesel to the produced biodiesel, the total volume of B5 is 1,200,000 L for *B. braunii*. The energy content of the total scenario is 98.6% B5 and 1.4% CBG for *B. braunii.* The conventional diesel within the B5 blend represents 94.1% of the total energy. Biodiesel from the generic strain is blended to produce 880,000 L of B5. The total energy content is 97.1% B5 and 2.1% CBG, and conventional diesel represents 92.7% of the total energy in the generic strain fuel mix. Calculations were performed using the heating values of biodiesel, biomethane, and diesel as 35.97 MJ/L, 8.96 MJ/L, and 36.14 MJ/L respectively [9].

The emission data for each conventional fuel are reported as life cycle emissions from production and combustion specific to Thailand. Data on the life cycle of natural gas and diesel is taken from Phumpradab et al. [34], Sheehan et al. [28] and Argonne GREET [9], and adapted to Thailand when necessary.

Below summarized in Figs. 3-4, algal fuels and their equivalent conventional fuels are compared by Global Warming Potential (GWP) in kg CO_2-eq, Acidification Potential (AP) in kg SO_2-eq, Photochemical Ozone Creation Potential (POCP) in kg C_2H_4-eq, and Eutrophication Potential (EP) in kg PO_4-eq.

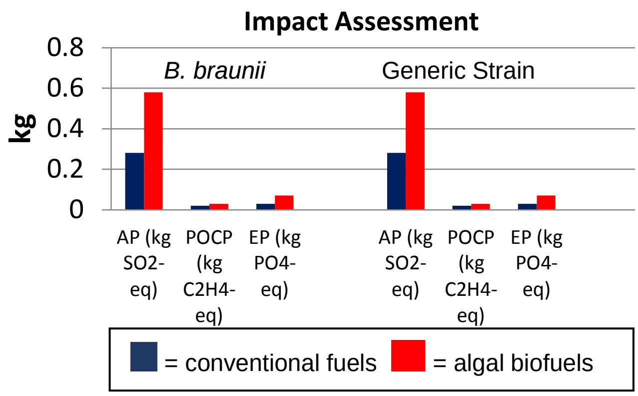

Figure 3. AP, POCP, EP of *B. braunii* and Generic strain-derived B5 and CBG and conventional diesel and CNG.

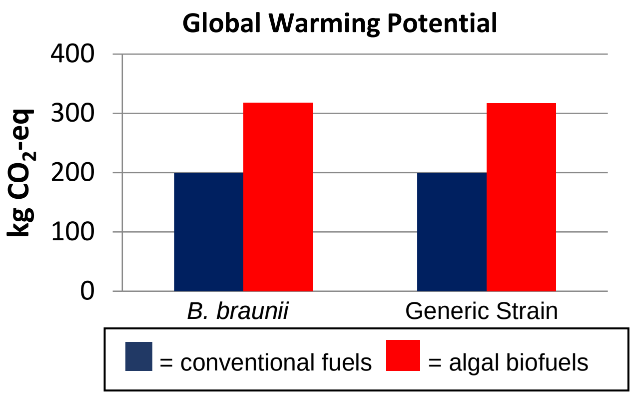

Fig. 4. Global Warming Potenntial (GWP) for *B. braunii* and Generic Strain-derived biofuels as compared with conventional diesel and CNG.

Table 5: *Energy inputs, energy outputs, NER, and VKT for all biofuel production scenarios*

Scenario	Strain	Primary Energy Input (MJ)	Fuel Energy Output (MJ)	NER	VKT
1	*B. braunii*	2,420,000	2,430,000	1.00	1,160,000
2		2,000,000	2,520,000	1.26	1,220,000
3		1,230,000	1,920,000	1.56	936,000
1	Generic	2,330,000	2,400,000	1.03	1,140,000
2		1,970,000	2,470,000	1.25	1,200,000
3		1,230,000	2,010,000	1.63	976,000

As shown in Figs. 3-4, algae fuels have a greater environmental impact than the conventional fuel option for all impact categories. The higher impact from algae can be explained by the greater life cycle energy input required per energy output, represented as the process energy. Conventional low sulfur diesel has a process energy requirement of 0.209 MJ/ MJ fuel output, while, for example, the algae fuels produced from *B.braunii* in Scenario 2 have a process energy requirement of 0.790 MJ/MJ fuel output [28]. Emissions from electricity production make up a large portion of the algal fuel emissions. For *B.braunii* scenario 2, electricity makes up 87.4% of the total process energy demand, and the emissions from electricity comprise 30% of the total life cycle GWP.

5. Land Available for Algae Cultivation

Using aerial photography, the seven existing wastewater treatment plants (WWTPs) in Bangkok were analyzed for undeveloped surrounding land area that could be used for algae cultivation in raceway ponds. Of the seven WWTPs in Bangkok, only two have sufficient area available for algae production: Nong Khaem (12.2 ha of undeveloped land) and Thung Khru (8.5 ha of undeveloped land). Therefore, the total potential land area for algae production in Bangkok was estimated to be 20.7 ha.

The petroleum fuel displaced by algal biofuel production utilizing these 20.7 ha is given in Table 6. It is assumed in this study that current diesel and CNG usage is the same as 2007 usage. The percentage of petroleum fuels displaced is less than 1% for all fuels from either strain of algae.

Because the land area available within Bangkok can only produce enough algae fuel to offset a small percentage of Bangkok's petroleum fuel use, it is more reasonable to use land area outside of Bangkok. The present study assessed the available land at WWTPs in all of Thailand and applied that potential area to fuel production values. It was assumed that the potential area surrounding WWTPs outside of Bangkok was two times that of those found within the city limits. Using this assumption, the potential available hectares for all of Thailand is 512 ha. The present study also assumes that the algal biofuels produced outside of Bangkok will be transported to Bangkok and used within the city since majority of transportation fuels are used in Bangkok. Applying this potential land to production of algal biofuels, the liters and percentage of diesel and CNG displaced in Bangkok are reported in Table 6. The percentage of CBG produced if land in WWTPs outside of Bangkok were used increased to 8.7% and 14.0% for the two algae strains. While this is an increase in the amount of fuel produced, when applied to the potential % VKT displaced based on Bangkok's driving cycle, the CBG produced from algae still accounts for less than 1% offset. The % VKT displaced for Scenario 2 and the two types of fuel is depicted in Table 7.

The percentage of diesel that can be replaced using available land in all of Thailand is less than 1% so the present study assessed the necessary land needed to replace 20% of diesel and CNG use in Bangkok. For 20% of Bangkok's diesel use to be displaced, 3,740,000,000 L of biodiesel would need to be produced. This amount of biodiesel would require 65,000 ha of land if produced from *B. braunii* or 87,900 ha if produced from the generic strain. To replace 20% of CNG use, 76,600,000 L of CBG are needed, requiring 1,170 ha of land for *B.braunii* or 698 ha for the generic strain. Table 6 below shows values for fuel displacement in both Bangkok and Thailand by algal biofuels in Scenario 2.

6. Discussion and Conclusions

The purpose of this study was to determine the feasibility of displacing conventional transportation fuels with algae produced fuels in Bangkok and to compare various biofuel production pathways. The fuel production pathways were first compared based on their NER and VKT. The results for both strains showed the highest VKT from the production of biodiesel and biomethane (fuel production Scenario 2). The highest NERs were obtained from the production pathway involving only biogas production (fuel production Scenario 3). As the purpose of the study was to displace conventional fuels, VKT was determined to have a higher significance; however, the lower NER is important for production considerations. The energy intensive process for biodiesel production shows significant room for improvement in terms of energy reduction, specifically in the harvesting and lipid extraction stages. As improvements are made, biodiesel production should be reevaluated to determine NER improvements which would make it more feasible for production.

The primary energy input in the production of ethanol was lower than the fuel energy yield with both *B.braunii* and the generic strain. The production process for ethanol from algae was found to require more energy than can be obtained from the fuel source. The processes involved are saccharification, fermentation, distillation, dehydration, and blending. The distillation process alone requires over 14 MJ/L ethanol produced and the energy density of ethanol is 21.3 MJ/L. It is concluded from this energy balance that while ethanol may be a useful fuel energy source in some scenarios, it is not energy favoring when being produced from algae. Ethanol production is, therefore, not recommended with algae strains containing carbohydrate contents similar to that found in the strains used in the present study.

Table 6. Bangkok fuel displacement using available wastewater treatment plants in Bangkok versus available wastewater treatment plants in all of Thailand assuming fuel use based off of the transportation needs of Bangkok.

	Fuel Type	Fuel Produced by S2, BB (million L)	% Fuel Displaced by S2, BB	Fuels Displaced by S2, GS (million L)	% Fuel Displaced by S2, GS
Bangkok Only	Biodiesel	1.20	0.00640	0.955	0.00510
	CBG	1.40	0.350	2.27	0.590
All of Thailand	Biodiesel	29.6	0.15	22.5	0.12
	CBG	34.2	8.7	57.3	14.0

Table 7. Vehicles Kilometer Traveled (VKT) displacement using available wastewater treatment plants in Bangkok versus available wastewater treatment plants in all of Thailand assuming fuel use based off of the transportation needs of Bangkok.

	Fuel Type	VKT by S2, BB (million km)	% of Bangkok's total VKT Displaced by S2, BB	VKT by S2, GS (million km)	% of Bangkok's total VKT Displaced by S2, GS
Bangkok Only	Biodiesel	20.9	0.0115	16.7	0.00915
	CNG	24.4	0.0134	9.87	0.00542
All of Thailand	Biodiesel	516	0.284	393	0.216
	CNG	597	0.328	249	0.137

Algal biomethane has an efficient conversion process, requiring low input energy. Biomethane production shows room for improvement primarily in actual yield of theoretical methane production. Options such as co-digestion with proven feedstocks should be considered to improve methane yield. While algal biomethane production was consistently high throughout the fuel production scenarios, the reference flow for traveling 1000km is much higher than that of the other fuels, rendering the potential for CBG to offset Bangkok's petroleum needs relatively low.

The present study noted no significant differences between the chosen strains. This suggests a local strain grown with minimally intensive cultivation has the potential to have similar yields as a specific strain chosen for biodiesel cultivation. This is due to the increase in growth rate seen in strains that do not favor lipid production.

In comparison to conventional fuels, B5 and biomethane produced in Scenario 2 showed an increase in total process emissions. The algae biofuels had higher impact potentials for all the given categories, showing a decrease in overall environmental benefit from algal biofuels. The increase in pollutants is due to the high process energy demand of algae biofuel production, which is significantly higher than that of conventional diesel. The energy demanded is supplied primarily by the Thai grid which lacks pollution control or efficient technologies and thus contributes large amounts of pollutants per kWh. These results are extremely important and show that although some algae biofuels yield more energy than is inputted, they are not an environmentally friendly alternative to conventional transportation fuels.

Land use constraints in Bangkok suggest the minimal impact which algae fuels could have on overall fuel consumption. There is more land available outside of Bangkok, but as wastewater treatment plants are only available in urban areas, available land will likely be a problem in any location. While there may be sufficient land to offset 10% of Bangkok's diesel or CNG usage, land close to wastewater treatment plants is a limiting factor for algal biofuel production.

Based on the findings of this study, utilizing the production of transportation fuels from algae at most can replace only 0.13% when considering the potential VKT of the second fuel production scenario. Biomethane and biodiesel would not, using current wastewater treatment ponds in Thailand, replace a significant part of Bangkok's fossil fuel needs. The liters produced of CBG were consistently high but the energy density is relatively low and the amount that algal biomethane offset Bangkok's petroleum needs was in turn, low. One suggestion for moving forward is to focus on a more efficient way to produce ethanol. It was not included in our final production scenario because the energy production chain was not favoring. If the process was improved for obtaining ethanol from algae, its ability to offset Bangkok's petroleum needs could be greatly increased. Most cars used today can utilize gasoline that contains 10-15% ethanol fuel so if the production chain for this was decreased and the energy inputs reduced, producing ethanol could be more energy favorable, and used throughout Bangkok as a transportation fuel. Additionally, the main reason that this LCA puts a "red flag" on algal biofuels is that the emissions were higher for algal biofuels production when compared to traditional fuels such as gasoline and diesel. This could due to the many refining processes necessary for algal biofuel production. Suggestions for further research are to attempt a pilot scale experiment to actually produce biofuels from algae because this LCA is based on hypothetical calculations. In order to determine if there is a future in this 4th generation biofuel, methods that can produce biofuels need to be developed and improved to find the most energy and cost effective ways to use abundant microalgae.

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