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Life Cycle Assessment of Biodiesel Production from Microalgae in Thailand: Energy Efficiency and Global Warming Impact Reduction

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In this study, a life cycle assessment (LCA) technique based on ISO 14040 series was performed to evaluate biodiesel production from freshwater microalgae *Scenedesmus armatus* in terms of energy efficiency (Net Energy Ratio or NER) and environmental impact (Global Warming Potential or GWP). The system boundary covered the entire life cycle of microalgae-based biodiesel, which was divided into four distinct steps: cultivation, harvesting, oil extraction, and transesterification. Based on a functional unit of 1 MJ biodiesel, NER was found to be 0.34 and 0.19 for mass allocation and energy allocation, respectively. This energy deficit (NER<1) for both allocation methods was due to the high energy input required to culture microalgae. However, CO_2 uptake in biomass agriculture leads to better performance in global warming potential (GWP) when compared to conventional diesel and biodiesel produced from rapeseed and soybean. This is a result of the cultivation process in which microalgae can fix up to 25 % of net greenhouse gas emissions (kg CO_2 equivalent). Sensitivity analysis showed that increasing in biomass concentration can improve not only net energy ratio (NER) but also global warming potential (GWP).

1. Introduction

Due to fossil fuel depletion and global warming, biofuel has been pointed out as a promising alternative energy because CO_2 emitted from the combustion is offset by CO_2 fixed in the atmosphere via photosynthesis. The process is often referred to as Carbon Neutral process. As a result of mass production of the first generation biofuel, its ability to achieve the target of petroleum substitution tends to be limited due to the competition of biofuel with food crop for land use. The rising of food price is also due to the increase in the production of biofuel. Many problems and concerns associated with the first generation biofuel can be addressed by the second generation biofuel which is manufactured from non-food crop feedstock using advanced technology. Although the pilot plants and demonstration facilities are being developed, the production of the second generation biofuel suffers with cost effectiveness due to technological barrier and feedstock collection network. Microalgae are an attractive source of biomass since they do not compete with any food crops, have the ability of CO_2 fixation, and have much higher production yield per area than terrestrial crops as shown in Table 1.

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Therefore, microalgae-based biofuel which is considered the third generation biofuel has a great promise as a sustainable alternative to conventional transportation fuel. In Thailand, several institutions have already started to investigate the production of biofuel from microalgae in various aspects including strain selection and technological development. However, there is no study in Thailand on energy and environmental evaluation of the microalgae system for biofuel production. Thus, at this stage it is very important to assess biofuel production from microalgae in energy and environmental aspects throughout its life cycle. The aim of this study is to employ life cycle assessment (LCA) technique based on ISO 14040 series to evaluate the biofuel production from microalgae in terms of energy efficiency (Net Energy Ratio or NER) and environmental impact (Global Warming Potential or GWP). It is also expected that the results can provide baseline information for the production of biofuel from microalgae to best suit the country in the most environmentally friendly way.

Table 1: Comparison of average oil yield between microalgae and other feedstocks (Riesing, 2009)

Feedstock	Yield (gallons of oil per acre per y)
Corn	18
Soybean	48
Safflower	83
Sunflower	102
Rapeseed	127
Oil palm	635
Microalgae	5,000-15,000

2. Methodology

2.1 Goal and scope

The goal of this study is to perform a life cycle assessment (LCA) of biodiesel production from microalgae in Thailand based on ISO 14040 in order to evaluate the energy efficiency and environmental impact of microalgae-based biodiesel. The energy efficiency is expressed in terms of Net Energy Ratio (NER) while Global Warming Potential (GWP) is a key factor to demonstrate the environmental impact. Additionally, comparison between microalgae-based biodiesel and conventional fossil diesel or other types of biodiesel is necessary to provide suggestion for improving the energy efficiency and environmental performance of this kind of biodiesel.

2.2 Functional unit

In life cycle assessment (LCA), the functional unit provides a reference to which the inputs and outputs are related. Since biodiesel has a similar combustion characteristic with conventional fossil diesel, the functional unit for this LCA study is 1 MJ of energy from microalgal biodiesel. This justifies a direct and fair comparison of microalgae-based biofuel to other fuels based on their calorific value.

2.3 System boundary

The system boundary used in this study covers all processes in the entire life cycle of the production of biodiesel from microalgae including four distinct stages: cultivation, harvesting, oil extraction, and transesterification as shown in Figure 1.

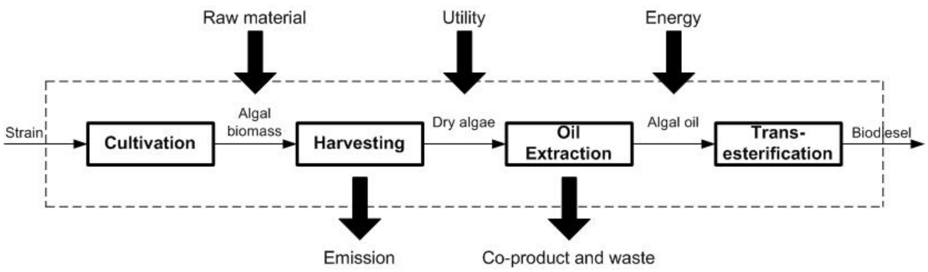


Figure 1: System boundary of biodiesel production process from microalgae.

2.4 Life cycle inventory: data source and software support

Since microalgae are not currently grown on a commercial scale for the production of biofuel in Thailand, data were collected from several sources. Some relevant data were extracted from literatures whereas data for cultivation and harvesting stage were collected from Biochemical Engineering laboratory, Faculty of Engineering, Chulalongkorn University with the maximum capacity of 100 L of microalgae. SimaPro 7.1 program with Cumulative Energy Demand and CML 2 baseline 2000 method was used to compute energy demand and environmental impact potentials. The proposed process flow diagram for the production of 1 MJ algal biodiesel from *Scenedesmus armatus* is shown in Figure 2.

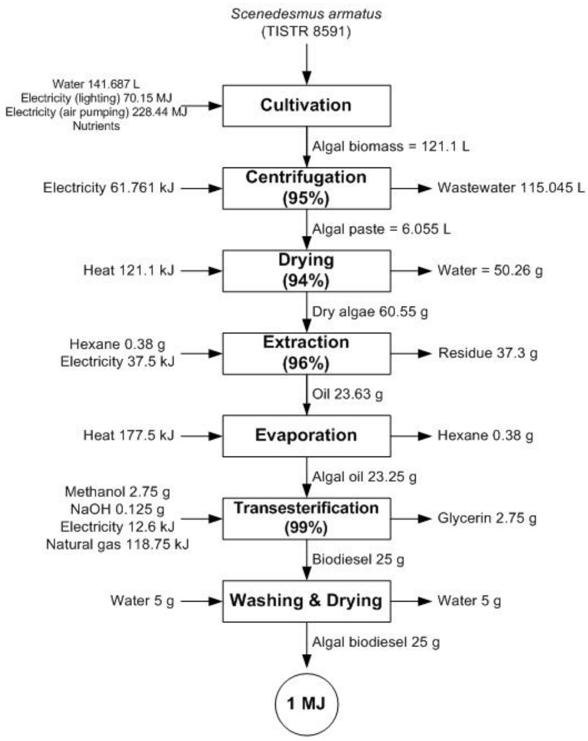


Figure 2: Process flow diagram for the production of 1 MJ microalgal biodiesel from Scenedesmus armatus.

2.5 Life cycle inventory: allocation

When biodiesel is produced, residue and glycerol are co-generated. In life cycle assessment (LCA), allocating material and energy inputs as well as environmental emissions between main product and co-product is a necessary issue. In this LCA study, both mass allocation and energy allocation were applied and compared. The partitioning ratios between main product and co-product for both allocation methods are shown in Table 2.

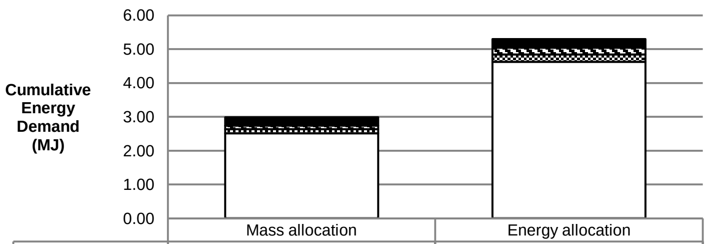
Table 2: Partitioning ratios between main product and co-product

Product/Co-product	Allocation		References
	Mass	Energy	
Oil Extraction			
Algal oil	38.4 %	68.1 %	Hou *et al.*, 2011
Residue	61.6 %	31.9 %	Hou *et al.*, 2011
Transesterification			
Algal biodiesel	90.1 %	93.5 %	Khoo *et al.*, 2011
Glycerin	9.9 %	6.5 %	Palmer, 2007

3. Results and discussion

3.1 Life cycle energy analysis

A life cycle energy analysis has been performed to analyze the total energy consumption of 1 MJ of biodiesel produced from microalgae. The cumulative energy demand (CED) shown in Figure 3 includes energy used at the facility and energy required for the production of the required inputs such as nutrients. The result showed that cultivation process makes up the largest proportion of the energy consumption. Up to the cultivation stage, the energy requirement amounted to be 2.51 and 4.62 MJ per MJ biodiesel for mass allocation and energy allocation, respectively. This process comprised more than 80 % of the entire life cycle energy input. The majority of the energy consumed during the cultivation process comes from electricity required for lighting and air pumping. With other three processes, the energy requirement totalled to be 2.98 MJ per MJ biodiesel for mass allocation and 5.29 MJ per MJ biodiesel for energy allocation.



	Mass allocation		Energy allocation	
Transesterification	MJ	0.25	MJ	0.26
Oil Extraction	MJ	0.11	MJ	0.20
Harvesting	MJ	0.12	MJ	0.22
Cultivation	MJ	2.51	MJ	4.62

Figure 3: Cumulative energy demand in MJ per MJ biodiesel

To evaluate the feasibility and competitiveness of the microalgae-to-biodiesel process, a comparison of net energy ratio (NER) has been made with a conventional petroleum-to-diesel process and other studies using other feedstocks. Net energy ratio (NER) is defined as a ratio of energy output to energy input. Based on a functional unit of 1 MJ biodiesel, NER for biodiesel produced from microalgae was found to be 0.34 and 0.19 for mass allocation and energy allocation, respectively. In comparison with biodiesel production from *Nannochloropsis salina* studied by Batan *et al.* (2010), the resulting NER was 0.93 MJ of energy consumed per MJ of energy produced. This meant that our process and their process are not energy efficient as NER<1. The comparison for net energy ratio (NER) is presented in Figure 4. The result showed that the microalgal biodiesel is out-competed by other biofuels, even convention fossil diesel. Additionally, the energy balance resulted in a deficit of -1.98 MJ for mass allocation and -4.29 MJ for energy allocation. As discussed earlier, this energy deficit was due to the high energy input required to culture microalgae and relatively low overall yield.

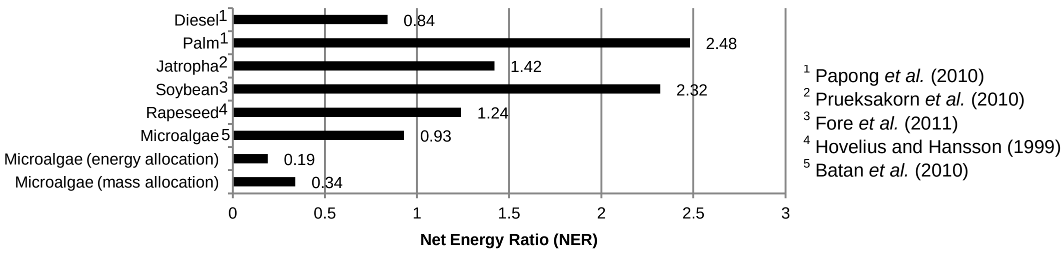


Figure 4: Comparison of net energy ratio (NER) based on 1 MJ biodiesel

3.2 Life cycle impact assessment

Potential environmental impacts of microalgae-to-biodiesel process have been assessed by using the CML 2 baseline 2000 method. As stated earlier, global warming potential (GWP) has been focused in this study. Net greenhouse gas emissions for microalgae-to-biodiesel process was found to be 0.012 and 0.021 kg CO_2 eq. per MJ biodiesel for mass allocation and energy allocation, respectively. In addition, other impact categories including abiotic depletion, ozone layer depletion, human toxicity, photochemical oxidation, acidification, and eutrophication have been concerned. To gain a better understanding of advantages and drawbacks of microalgal biodiesel, the results have been compared to conventional diesel and biodiesel from other feedstocks. Since mass allocation has shown a better performance in NER, only this case is used in this comparative study. The comparison of environmental impacts generated by the production of 1 MJ of these fuels is presented in Figure 5. All impact categories were standardized with the value of the worst scenario of each impact in order to identify its potential. Therefore, maximum value of each category is treated as 100 %.

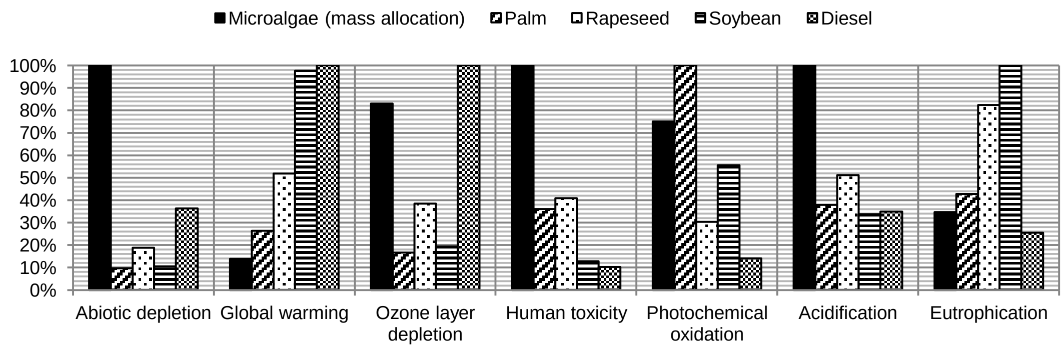


Figure 5: Comparison of environmental impacts based on 1 MJ biodiesel

The results showed that microalgal biodiesel appears as the worst case for abiotic depletion, human toxicity, and acidification. On the other hand, it showed very low impact for global warming, and average impact for ozone layer depletion, photochemical oxidation, and eutrophication. Lower eutrophication potential can be attributed to a better control of nutrients due to the absence of pesticides or toxic agrochemicals in microalgae cultivation compared to plant cultivation. However, human toxicity potential is largely contributed by chemicals production. As a result of acidic substances, acidification potential has increased. Moreover, the high demand of hexane for oil extraction leads to high photochemical oxidation potential. According to heat and electricity requirements, abiotic depletion, ozone layer depletion, and global warming potential have been developed. The primary reason of a significant decrease in global warming potential is the large amount CO_2 uptake of 1.83 kg CO_2 per kg dry microalgae during cultivation process (Chisti, 2007). As a result, microalgae can fix up to 25 % of net greenhouse gas emissions (kg CO_2 equivalent) in this LCA study. The allocation of co-product also shared all environmental burdens. For example, global warming potential was reduced by 64 % and 36 % as a result of mass allocation and energy allocation, respectively. The analogous results were observed in other impact categories as well.

3.3 Sensitivity analysis

To improve the net energy ratio (NER) of microalgae-to-biodiesel process, sensitivity analysis of biomass concentration was performed. The results were compared to the base case scenario in order to gain a better understanding in how the parameter affects the performance of the microalgae-based biofuel production system. According to Chisti (2007), algal biomass concentration can be as high as 4 g/L for photobioreactor facility. Since the final biomass concentration used in this study was 0.5 g/L, the biomass concentration was varied from 0.5 to 4.0 g/L in the sensitivity analysis by keeping other parameters constant. Figure 6 shows the net energy ratio (NER) and global warming potential (GWP) for the biomass concentration of microalgae ranging from 0.5 g/L to 4 g/L.

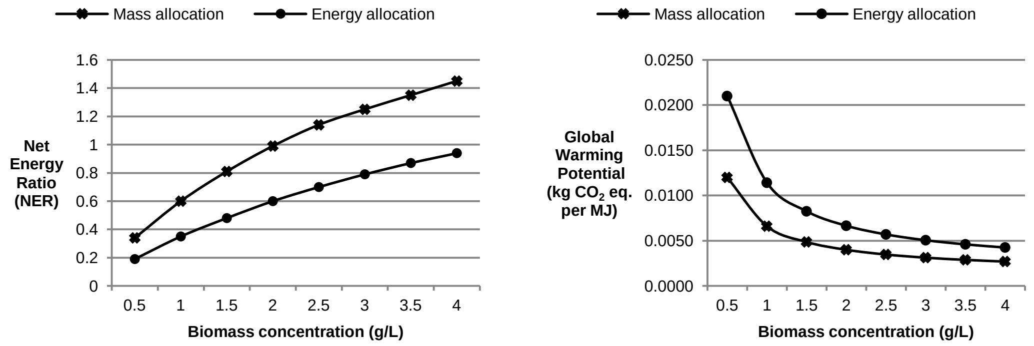


Figure 6: Sensitivity analysis of biomass concentration in terms of net energy ratio (NER) and global warming potential (GWP)

It can be obviously seen that biomass concentration as significant effect on both net energy ratio (NER) and global warming potential (GWP). The net energy ratio (NER) greatly increases with increasing biomass concentration and reaches the value of 1 at biomass concentration of 2 g/L for mass allocation. However, the net energy ratio still cannot reach the value of 1 in case of energy allocation. For global warming potential (GWP), GWP decreases sharply for biomass concentration in the range of 0.5-2.0 g/L. Beyond this concentration, GWP decreases but only slightly as shown in Figure 6.

4. Conclusions

In this study, the LCA methodology was performed to evaluate the energy efficiency and environmental performance of biodiesel produced from microalgae. Based on a functional unit of 1 MJ biodiesel, NER was found to be 0.34 and 0.19 for mass allocation and energy allocation, respectively. The main bottleneck of the microalgae-to-biodiesel production lies in the energy intensive process of cultivation. The huge energy demand in cultivation is the main challenge that has to overcome in order to make the value chain of microalgae-to-biodiesel feasible and practical. The impact assessment results indicated that producing biodiesel from microalgae as a replacement of fossil diesel contributes to the reduction of global warming potential, mainly due to the CO_2 uptake via photosynthesis during biomass agriculture. Sensitivity analysis showed that the application of different allocation methods affects the LCA outcomes. The results from sensitivity analysis showed that increasing in biomass concentration can improve not only net energy ratio (NER) but also global warming potential (GWP).

5. Acknowledgements

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