CHAPTER IV
RESULTS AND DISCUSSION

4.1 Life Cycle Inventory

4.1.1 Cultivation

The freshwater green microalgae strain *Scenedesmus armatus* (TISTR 8591) shown in Fig. 4.1 was selected for this system because of its high lipid content and high biomass productivity. Colonies of 2, 4, 8 cells attach side by side and arrange linearly or slightly zigzag. Cell body is elongated ellipsoidal in shape with both ends rounded. In general, size is 10-20 μm long and 3.5-8 μm wide. There are spiny projections (8-15 μm long) at terminal cells in many species. Cell wall is usually smooth, but in some species it is granulated or dented or ridge (Smith, 1995).

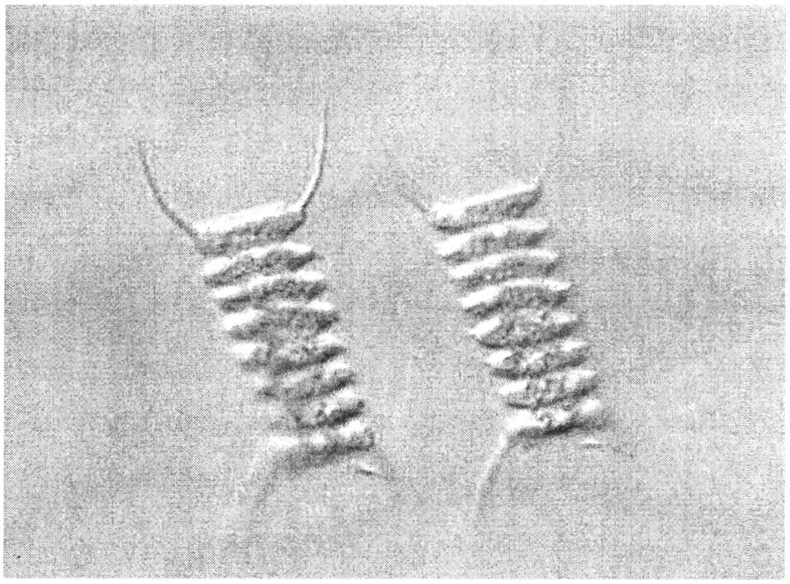


Figure 4.1 *Scenedesmus armatus* (Smith, 1995).

Under certain condition. *Scenedesmus armatus* can achieve a lipid content of 40 % by dry cell weight, and an average growth rate of 13.4 $g/m^2/day$ (Oilgae, 2011). Table 4.1 shows a chemical composition of *Scenedesmus armatus* expressed on a percentage of ash-free dry matter basis.

Table 4.1 Chemical composition of *Scenedesmus armatus*

Composition	Content (% ash-free dry weight)	References
Protein	45	See Appendix A
Carbohydrate	15	Rodjaroen *et al.*, 2007
Lipid	40	See Appendix A

Algal cultivation system at Biochemical Engineering laboratory, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University was used as a data collection site for the growth of microalgae. Fig. 4.2 shows the outdoor algal cultivation system of the location where data for cultivation were collected.

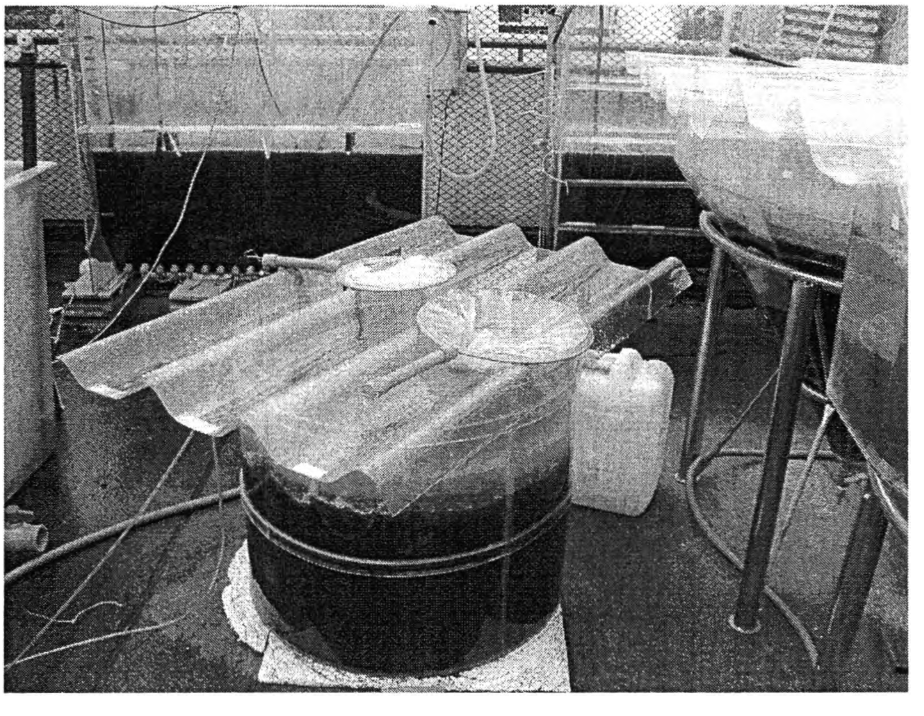


Figure 4.2 Photograph of outdoor algal cultivation system of Biochemical Engineering laboratory, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University.

To develop a mass culture from a strain of microalgae *Scenedesmus armatus*, the cultivation system was divided into four stages as shown in Fig. 4.3. The first three stages were conducted indoor with artificial illumination. The last stage was operated outdoor in a large tank utilizing natural light. All stages were in batch operation.

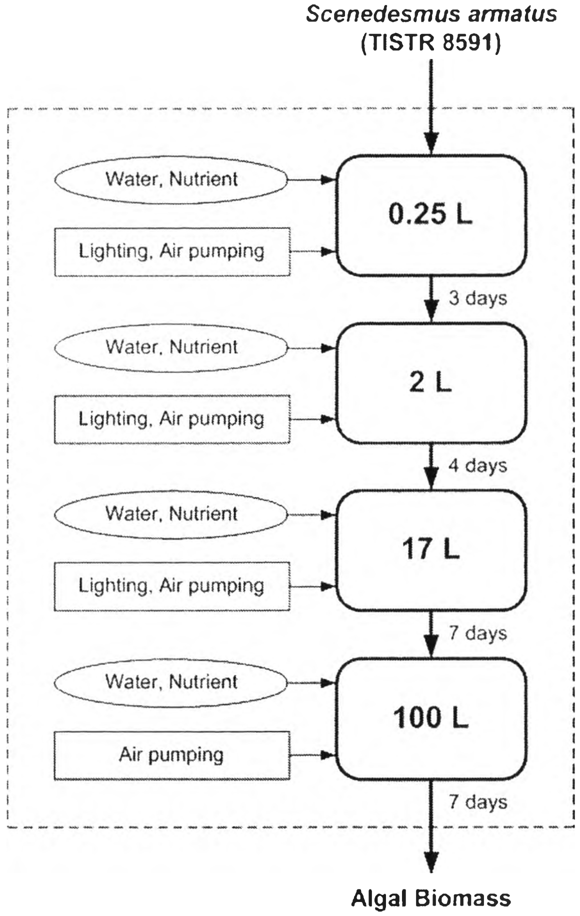


Figure 4.3 System boundary of cultivation process.

Nutrients and water were applied according to biological growth requirements. Electricity was used for air pumping and lighting. The process is assumed to operate 24 hours per day, with a final algal concentration of 0.5 g/L. Chisti (2007) estimated that 1 kg of dry microalgae biomass can effectively fix 1.83 kg of CO_2. The material inputs, material outputs, and energy inputs for the cultivation process are detailed in Table 4.2.

Table 4.2 Inventory data of cultivation process

Input Inventory						
Type	**Unit**	**Amount**				
		0.25 L	**2 L**	**17 L**	**100 L**	**Total**
Raw material						
Strain		*Scenedesmus armatus* (TISTR 8591)				
Water	L	0.25	1.75	15	100*	117
Chemical						
$NaNO_3$**	g	0.375	3	25.5	150	178.875
K_2HPO_4**	g	0.01	0.08	0.68	4	4.77
$MgSO_4 \cdot 7H_2O$	g	0.01875	0.15	1.275	7.5	8.94375
$CaCl_2 \cdot 2H_2O$	g	0.009	0.072	0.612	3.6	4.293
Citric acid	g	0.0015	0.012	0.102	0.6	0.7155
Ammonium ferric citrate**	g	0.0015	0.012	0.102	0.6	0.7155
$EDTANa_2$**	g	0.00025	0.002	0.017	0.1	0.11925
Na_2CO_3	g	0.005	0.04	0.34	2	2.385
H_3BO_3	g	7.15E-04	5.72E-03	4.86E-02	2.86E-01	3.41E-01
$MnCl_2 \cdot 4H_2O$**	g	4.53E-04	3.62E-03	3.08E-02	1.81E-01	2.16E-01
$ZnSO_4 \cdot 7H_2O$	g	5.50E-05	4.40E-04	3.74E-03	2.20E-02	2.62E-02
$Na_2MoO_4 \cdot 2H_2O$**	g	9.75E-05	7.80E-04	6.63E-03	3.90E-02	4.65E-02
$CuSO_4 \cdot 5H_2O$**	g	2.00E-05	1.60E-04	1.36E-03	8.00E-03	9.54E-03
$Co(NO_3)_2 \cdot 6H_2O$**	g	1.25E-05	1.00E-04	8.50E-04	5.00E-03	5.96E-03
Energy						
Electricity, for lighting	MJ	2.07	12.44	55.64	0	70.15
Electricity, for air pumping	MJ	25.92	34.56	60.48	67.68	188.64
Output Inventory						
Type	**Unit**	**Amount**				
Product						
Algal biomass	L	100				

*Already accounted for loss of evaporation.

**Based on chemical reaction balance (see Appendix B).

4.1.2 Harvesting

After cultivation, the removal of water from the harvested microalgae is required. The harvesting process at Biochemical Engineering laboratory, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University was also used as a model for this study. Algae harvesting is achieved by a two-step process which consists of centrifugation unit and drying unit as shown in Fig. 4.4. The centrifugation unit is used to separate algal biomass from its medium, while the drying unit is used to release water from the algal paste.

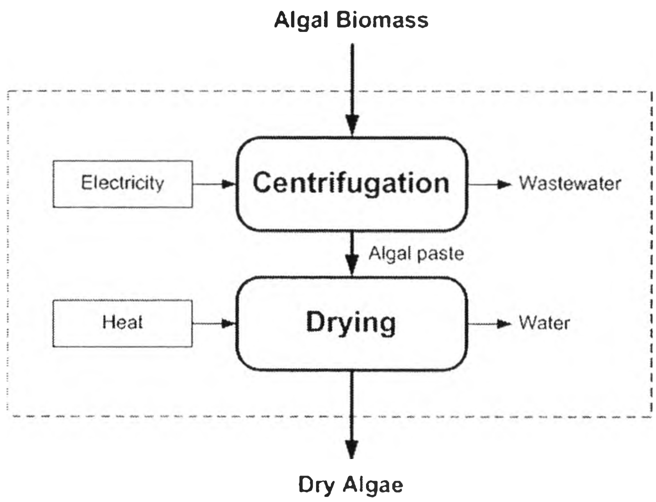


Figure 4.4 System boundary of harvesting process.

A centrifuge, Supra 22K, which consumes 3.4 kW was used to remove the majority of water for 5 minutes with 95 % efficient. Inside the centrifuge, the algal biomass was separated into a clear water phase and an algal paste. After that, the algal paste was discharged from the centrifuge and then fed directly to a dryer for drying. Heat was applied to dryer in order to remove moisture content from 92 % to 9 % with 94 % efficient. The energy consumption required for the harvesting process is summarized in Table 4.3.

Table 4.3 Inventory data of harvesting process

Input Inventory		
Type	**Unit**	**Amount**
Raw material		
Algal biomass	L	2000
Energy		
Electricity	MJ	1.02
Heat	MJ	2.00
Output Inventory		
Type	**Unit**	**Amount**
Product		
Dry algae	kg	1
Emission to water		
Wastewater	L	1900

4.1.3 Oil Extraction

For lipid extraction, data were extracted from literature (Lardon *et al.*, 2009). The process shown in Fig. 4.5 consists of two main units: extraction unit and evaporation unit for the recovery of solvent. In fact, three products are generated from the extraction unit which are algal oil, water, and residue. However, water is considered negligible in this study because of very low water content due to dry extraction method. It should be noted that the allocation of the product (algal oil) and co-product (residue) is needed and will be discussed later.

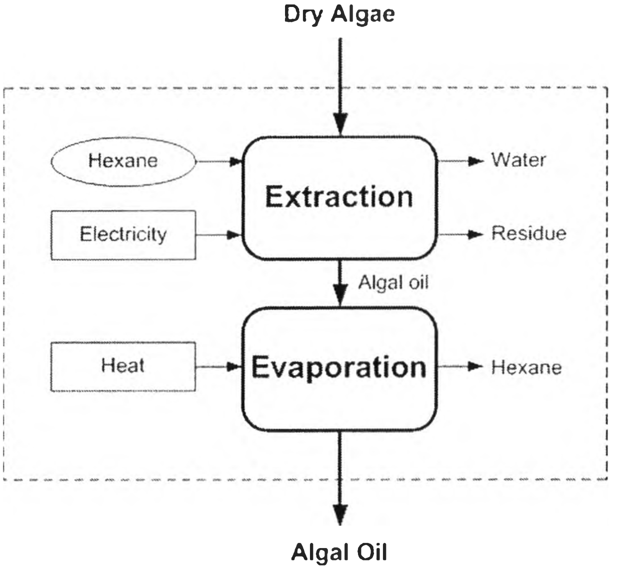


Figure 4.5 System boundary of extraction process.

The extraction system employed a pure solvent of hexane which was mixed with dry microalgae to extract triglycerides. Hexane extraction at 60 °C is assumed to recover as high as 96 % of the lipid present in the microalgae. Then the mixture was kept at room temperature for 24 hours for settling. The evaporation system is used for solvent recovery and oil separation. The extracted oil was evaporated to release hexane. It is assumed that no loss of algal oil occurred from the evaporation process. In addition, density of algal oil is assumed to be 0.93 kg/L (Sander and Murthy, 2010). Material and energy consumption for the extraction process is shown in Table 4.4.

Table 4.4 Inventory data of extraction process

Input Inventory		
Type	**Unit**	**Amount**
Raw material		
Dry algae	kg	2.6
Chemical		
Hexane	kg	0.016
Energy		
Electricity	MJ	1.61
Heat	MJ	7.63
Output Inventory		
Type	**Unit**	**Amount**
Product		
Algal oil	kg	1
Co-product		
Residue	kg	1.6

(Extracted data from Lardon *et al.*, 2009)

4.1.4 Conversion

Inventory data of conversion process were also extracted from literature (Parsons Brinckerhoff, 2011). The conversion process shown in Fig. 4.6 consists of both chemical unit and industrial unit which are required to convert the extracted microalgae oil into biodiesel via transesterification. The process required the reaction of triglyceride, which exists in the extracted microalgae oil, with methanol in the presence of catalyst, producing fatty acid methyl esters (biodiesel) and glycerin. Since no exact information has been published regarding to free fatty acid (FFA) content containing in *Scenedesmus armatus*, free fatty acid (FFA) was not considered in this study. Sodium hydroxide (NaOH) is selected as a basic catalyst for transesterification reaction. Finally, crude fatty acid methyl ester is treated by washing and drying to obtain biodiesel end product which is ready to be used. Additionally, allocation of the product (algal biodiesel) and co-product (glycerin) is required and will be discussed later.

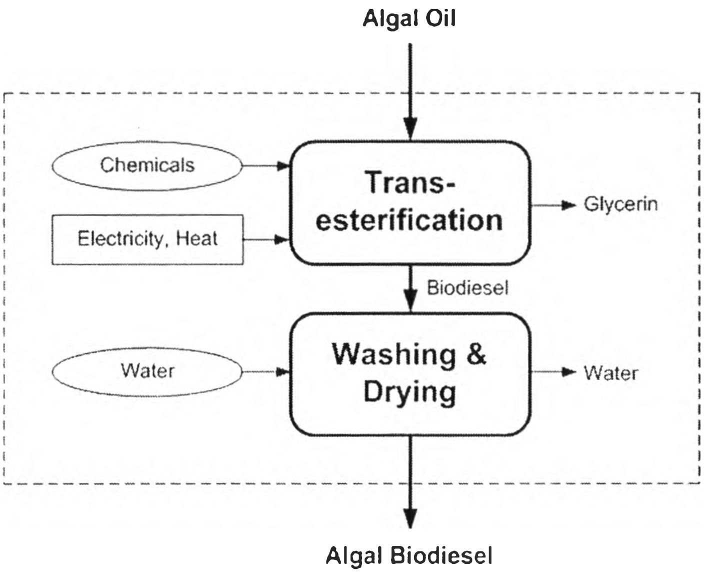


Figure 4.6 System boundary of conversion process.

Methanol and sodium hydroxide were mixed in proportion to the quantity of biodiesel produced, as shown in Table 4.5, and then stirred properly for 20 minutes and pre-heated until 60 °C in order to avoid formation of methanol vapor. After that, the mixture of catalyst (NaOH) and methanol was introduced into the algal oil in order to perform a transesterification reaction. In this study, it is assumed that 99 % of triglycerides were transformed into biodiesel and glycerin. The solution was kept at room temperature for 16 hours to settle the biodiesel and glycerin layers clearly. After biodiesel was separated, it was washed by water and dried by using keeping for 12 hours. No loss of algal biodiesel occurred from washing and drying process. Natural gas was used for heating process while electricity was used for mixing and transport. For the properties of the product, density of algal biodiesel is 0.87 kg/L (Sander and Murthy, 2010) and heating value of algal biodiesel is 40 MJ/kg (Khoo *et al.*, 2011).

Table 4.5 Inventory data of conversion process

Input Inventory		
Type	**Unit**	**Amount**
Raw material		
Algal oil	kg	0.93
Water	kg	0.20
Chemical		
Methanol	kg	0.11
Sodium hydroxide	kg	0.005
Energy		
Electricity	MJ	0.504
Natural gas	MJ	4.75
Output Inventory		
Type	**Unit**	**Amount**
Product		
Algal biodiesel	kg	1
Co-product		
Glycerin	kg	0.11

(Extracted data from Parsons Brinckerhoff, 2011)

4.1.5 Allocation

According to LCA methodology based on ISO 14040, when a process leads to the production of multiple products, an allocation is necessary in order to share the environmental burden between main product and co-products according to their relative content. In microalgae-to-biodiesel process, there are two primary co-products: residue (generated from the extraction stage) and glycerin (generated from the conversion stage). Three allocation methods have been applied to the microalgae-to-biodiesel process: mass allocation (Lardon *et al.*, 2009; Hou *et al.*, 2011), energy allocation (Lardon *et al.*, 2009; Batan *et al.*, 2010; Hou *et al.*, 2011), and economic allocation (Batan *et al.*, 2010). Since microalgae-based biodiesel is not commercial in Thailand at the present, only mass and energy allocation are performed in this study.

Mass allocation is done on a dry basis because the valuable products come from dry solid content. Energy allocation is based on the heating value of each main product and co-product as shown in Table 4.6. To understand the influence of different allocation methods, sensitivity analysis is required. Table 4.7 shows the comparison between main product and co-product for both allocation methods.

Table 4.6 Heating value of products and co-products

Product/Co-product	Heating value (MJ/kg)	References
Algal oil	37	Hou *et al.*, 2011
Residue	10.83	Hou *et al.*, 2011
Algal biodiesel	40	Khoo *et al.*, 2011
Glycerin	25.30	Palmer, 2007

Table 4.7 Partitioning ratios between main product and co-product

Product/Co-product	Allocation	
	Mass	Energy
Oil Extraction		
Algal oil	38.4 %	68.1 %
Residue	61.6 %	31.9 %
Transesterification		
Algal biodiesel	90.1 %	93.5 %
Glycerin	9.9 %	6.5 %

Fig. 4.7 and Fig. 4.8 show the proposed process flow diagram with mass and energy input-output for the production of 1 MJ algal biodiesel from *Scenedesmus armatus* for mass allocation and energy allocation, respectively.

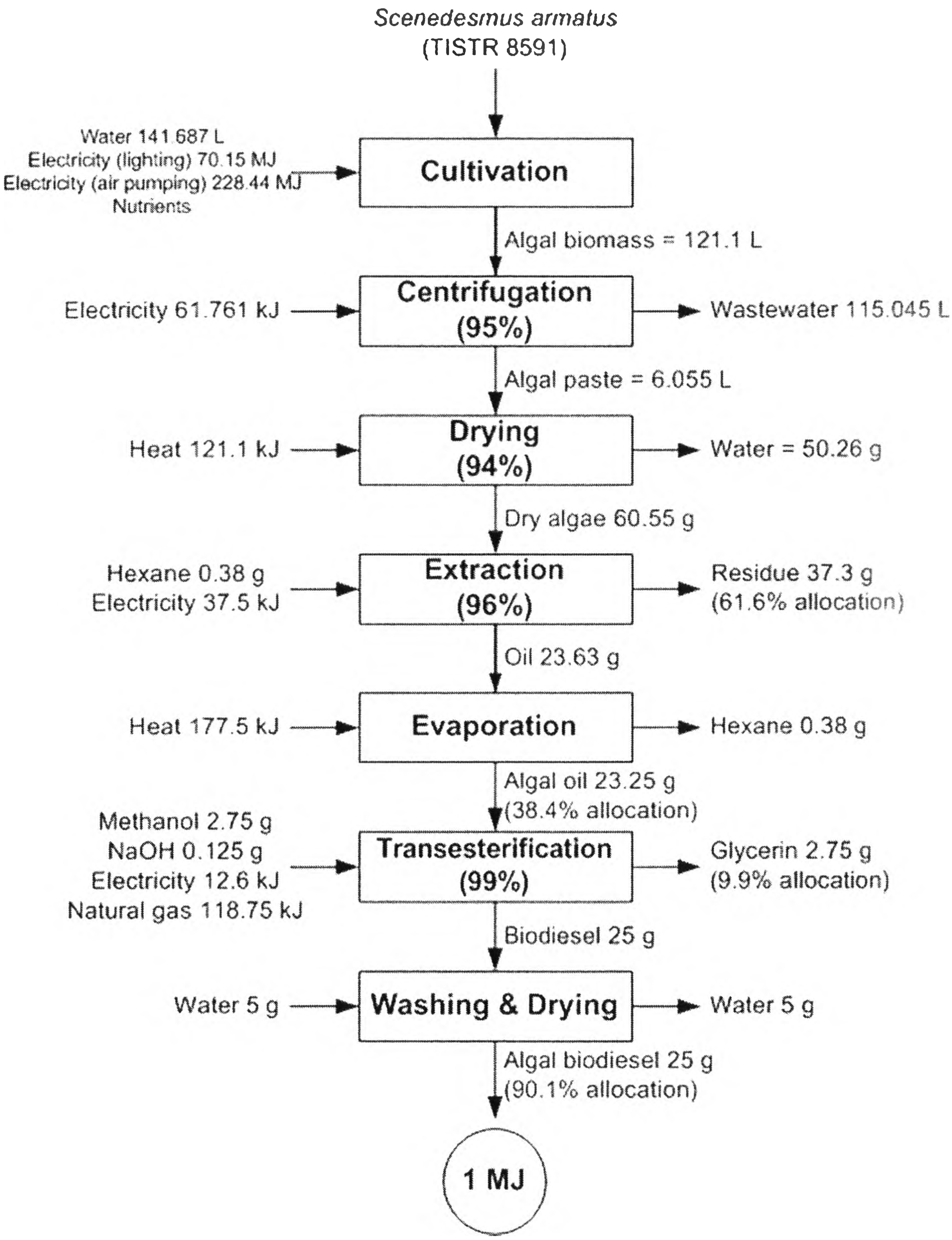


Figure 4.7 Process flow diagram for the production of 1 MJ algal biodiesel from *Scenedesmus armatus* for mass allocation.

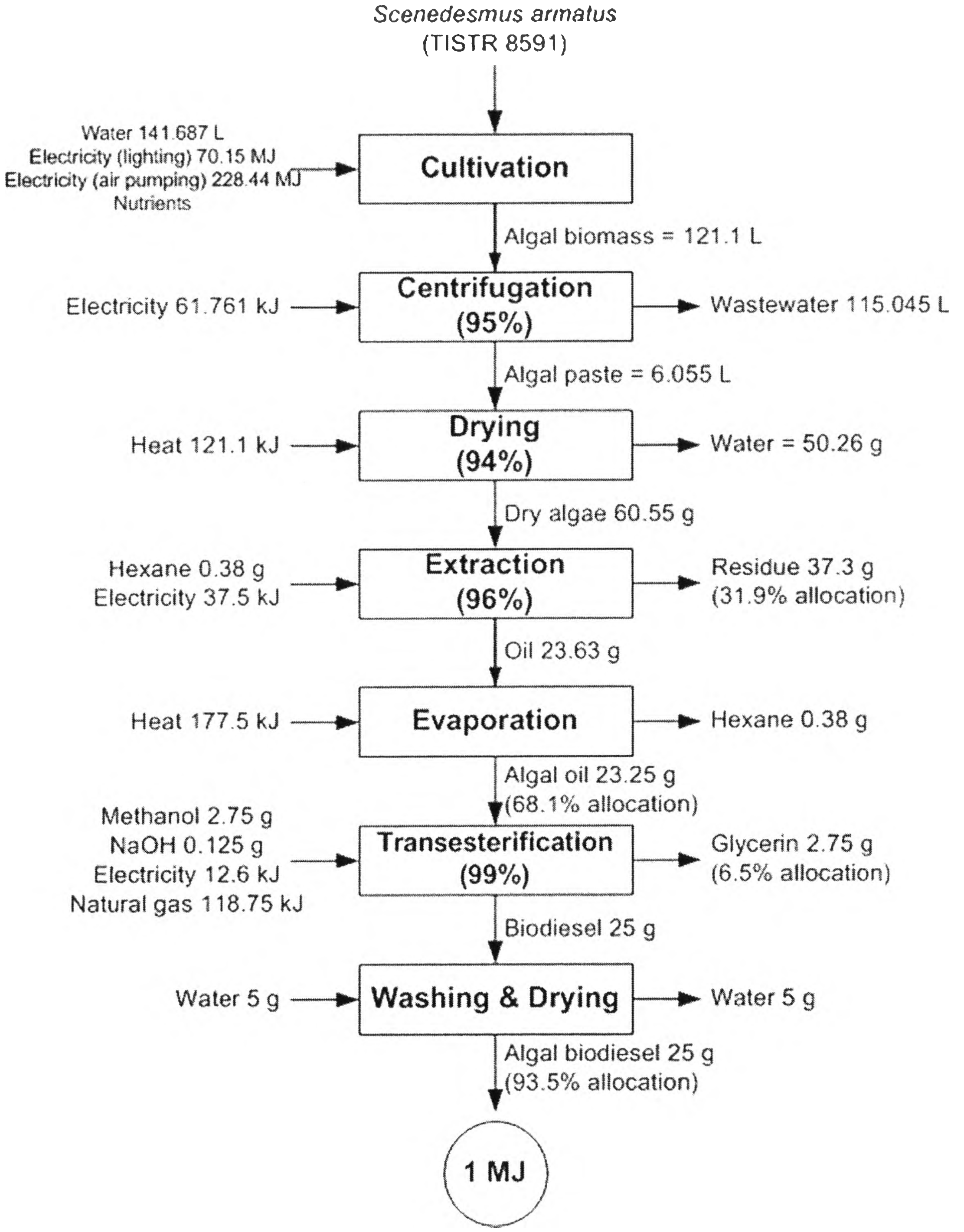
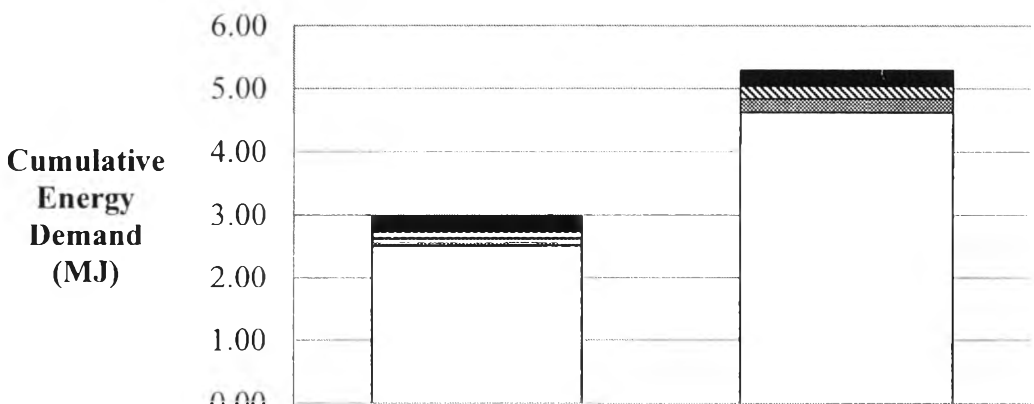


Figure 4.8 Process flow diagram for the production of 1 MJ algal biodiesel from *Scenedesmus armatus* for energy allocation.

4.2 Life Cycle Energy Analysis

4.2.1 Cumulative Energy Demand

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 Fig. 4.9 includes energy used at the facility and energy required for the production of the required inputs such as nutrients.



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

Figure 4.9 Cumulative energy demand in MJ per MJ biodiesel.

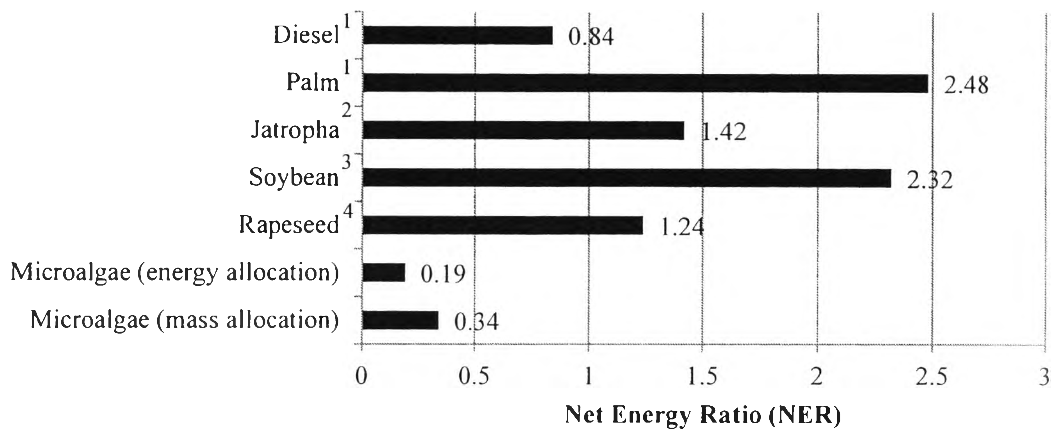
From Fig. 4.9, it can be observed that cultivation process makes up the largest proportion of the energy consumption. Up to the cultivation stage, the energy requirement amounted to be 2.51 and 4.62 MJ per MJ biodiesel for mass allocation and energy allocation, respectively. This process comprised more than 80 % of the entire life cycle energy. The majority of the energy consumed during the cultivation process comes from electricity required for lighting and air pumping. For other the three processes (i.e. harvesting, oil extraction, and transesterification), the energy requirement totaled to be 2.98 MJ per MJ biodiesel for mass allocation and 5.29 MJ per MJ biodiesel for energy allocation.

4.2.2 Net Energy Ratio

Net energy ratio (NER) is defined as a ratio of energy output to energy input. Any processes are considered to be efficient in terms of energy if value of NER is more than 1, and vice versa. 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 of producing biodiesel from microalgae and their process are not energy efficient as NER<1.

There are two major differences which are relevant to our NER result compared to their result. In Batan *et al.* (2010), *Nannochloropsis salina* was selected because of its high lipid content. Under laboratory conditions, *Nannochloropsis salina* can achieve a lipid content of 60 % by weight. As a result of higher lipid content, yield of the process will increase. In addition, since Batan *et al.* (2010) proposed an industrial-scale model, recycling of growth media has been included in the process. Therefore, the energy requirement for nutrient production will be decreased.

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 from various countries using other feedstocks. The palm and jatropha biodiesel data were referred to the production in Thailand (Papong *et al.*, 2010; Prueksakorn *et al.*, 2010). Soybean biodiesel data were from US (Fore *et al.*, 2011). Rapeseed biodiesel data were based on Swedish study (Hovelius and Hansson, 1999). Assessment of diesel is based on the inventory data in Ecoinvent database which was adjusted for Thailand situation (Papong *et al.*, 2010). The comparison for net energy ratio (NER) is presented in Fig. 4.10.



[1] Papong *et al.* (2010), [2] Prueksakorn *et al.* (2010), [3] Fore *et al.* (2011), [4] Hovelius and Hansson (1999)

Figure 4.10 Comparison of net energy ratio (NER) based on 1 MJ biodiesel.

From Fig. 4.10, it can be noticed 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. Another important reason is due to the fact that overall yield of this process is relatively low.

4.3 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. In addition, other impact categories including abiotic depletion, ozone layer depletion, human toxicity, photochemical oxidation, acidification, and eutrophication have been concerned. The overall results showed that cultivation process has the highest environmental impact in all impact categories. Most of the impacts are mainly driven by energy consumption and chemicals usage. Moreover, the allocation of co-product also shared all environmental burdens. Mass allocation showed a better performance than energy allocation in all impact categories.

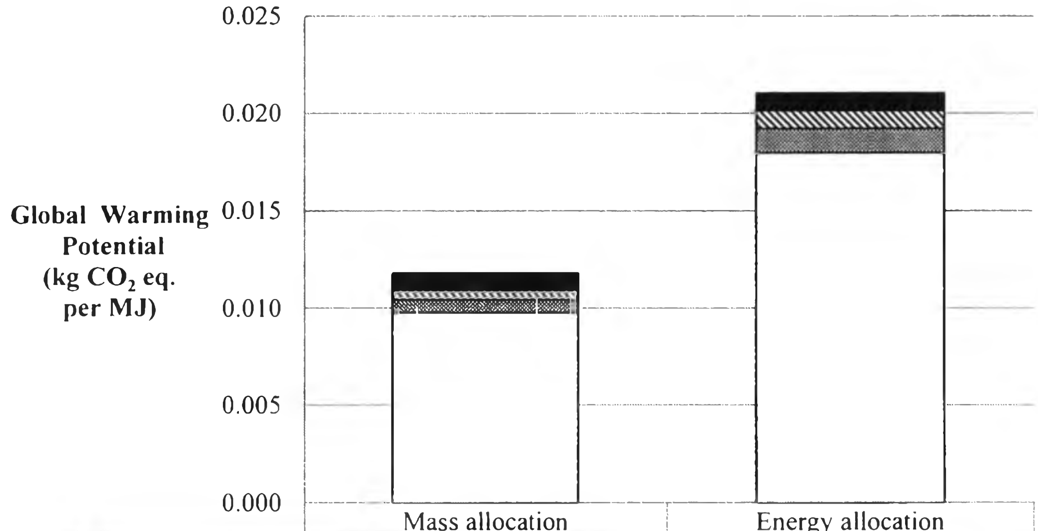
4.3.1 Global Warming Potential

The greenhouse gases considered in this study are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The concept of a global warming potential (GWP) has been used to enable different greenhouse gases to be compared with each other and expressed in terms of kilogram equivalent of CO_2. The GWP factors reflect the different extent to which gases absorb infrared radiation and the different time scale in which the gases are removed from the atmosphere. The GWP factors for a 100 year time horizon are summarized in Table 4.8

Table 4.8 Global warming potential (GWP) factors with a 100 year time horizon (Campbell *et al.*, 2011)

Gas	Global Warming Potential (100 year time horizon)
Carbon dioxide (CO_2)	1
Methane (CH_4)	21
Nitrous oxide (N_2O)	310

From energy requirements both in terms of heat and electricity, global warming potential have been evaluated. Fig. 4.11 shows that net greenhouse gas emissions contributed by 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. It is important to note that carbon dioxide sequestered in the biomass production during photosynthesis was already subtracted from the total greenhouse gas emissions for the cultivation process. When including CO_2 uptake credit from microalgae, the greenhouse gases emitted during the cultivation process were reduced by 25 % in terms of kg CO_2 equivalent. Global warming potential was also reduced by 64 % and 36 % as a result of mass allocation and energy allocation, respectively.

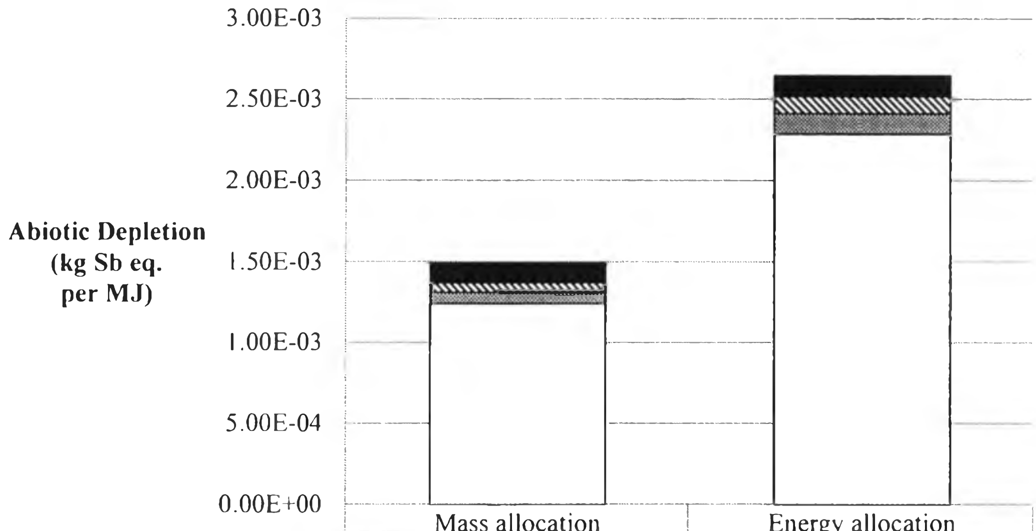


	Mass allocation	Energy allocation
■ Transesterification	8.764E-04	9.095E-04
Oil Extraction	5.001E-04	9.203E-04
Harvesting	6.777E-04	1.247E-03
□ Cultivation	9.761E-03	1.796E-02

Figure 4.11 Global warming potential (GWP) based on 1 MJ biodiesel.

4.3.2 Abiotic Depletion

Abiotic depletion is an indicator for the depletion of non-renewable natural resources such as mineral, ore, and fossil fuel. It indicates the ratio of extraction of resource relative to the ultimate reserve of the resource. Antimony (Sb) is chosen as a reference resource. To account for different types of abiotic resources the impact potential is computed by means of equivalency factors expressed in terms of kilogram equivalent of Sb. Fig. 4.12 shows the results of abiotic depletion impact on each process in the life cycle. Net abiotic depletion potential contributed by microalgae-to-biodiesel process was found to be 1.492E-03 and 2.645E-03 kg Sb eq. per MJ biodiesel for mass allocation and energy allocation, respectively. The abiotic depletion observed in this study has been a result of heat and electricity requirement, especially in the cultivation process. Natural gas and lignite coal are the main sources of energy used for heat production and electricity generation.

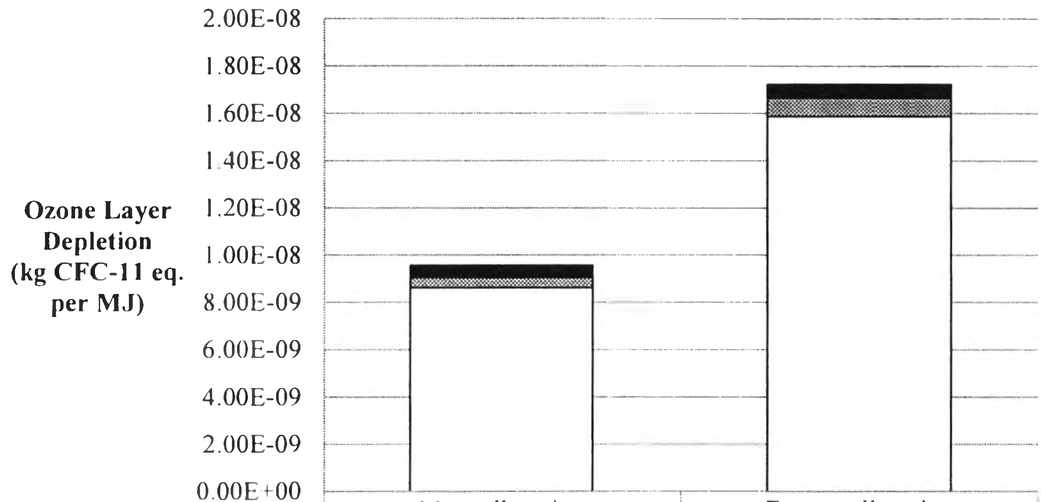


	Mass allocation	Energy allocation
■ Transesterification	1.243E-04	1.290E-04
▧ Oil Extraction	5.753E-05	1.059E-04
▨ Harvesting	6.848E-05	1.260E-04
□ Cultivation	1.241E-03	2.285E-03

Figure 4.12 Abiotic depletion potential based on 1 MJ.

4.3.3 Ozone Layer Depletion

Ozone layer depletion is caused by high level of chlorine and bromine compounds in the stratosphere. The main gas responsible for the ozone layer depletion is chlorofluorocarbon (CFC). Ozone layer depletion potential of different gases is measured as kilogram equivalent of trichlorofluoromethane (CFC-11). As a result of depletion of the ozone layer, more ultraviolet radiation comes to the earth and causes damage to living organisms and ecosystems. Fig. 4.13 shows the results of ozone layer depletion impact on each process in the life cycle. Net ozone layer depletion potential contributed by microalgae-to-biodiesel process was found to be 9.576E-09 and 1.724E-08 kg CFC-11 eq. per MJ biodiesel for mass allocation and energy allocation, respectively. The ozone depletion observed in this study comes from emissions of natural gas combustion used to provide heat as well as electricity used for biodiesel production.

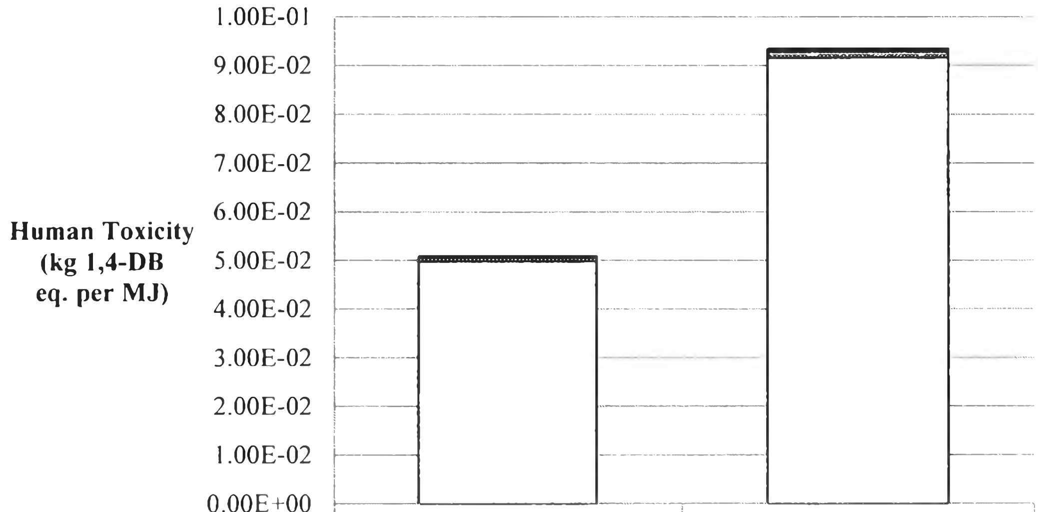


	Mass allocation	Energy allocation
Transesterification	4.805E-10	4.987E-10
Oil Extraction	5.297E-11	9.749E-11
Harvesting	4.146E-10	7.631E-10
Cultivation	8.627E-09	1.588E-08

Figure 4.13 Ozone layer depletion potential based on 1 MJ biodiesel.

4.3.4 Human Toxicity

Human toxicity refers to chemical, physical, or biological substances that may cause harmful effect to the human system. In fact, this potential effect depends on the actual exposure of human to the specific substances. Therefore, characterization factors are calculated to describe the fate, exposure, and effects of toxic substances for an infinite time horizon (over a period of 100 years). For each toxic substance, toxicity potential is expressed as kilogram equivalent of 1,4-dichlorobenzene (DB). Fig. 4.14 shows the results of human toxicity impact on each process in the life cycle. Net human toxicity potential contributed by microalgae-to-biodiesel process was found to be 5.096E-02 and 9.345E-02 kg 1,4-DB eq. per MJ biodiesel for mass allocation and energy allocation, respectively. The key indicator to this effect is the cultivation process. According to various chemicals used as a nutrient in the cultivation process, it can be concluded that chemicals production is a main contributor of this effect. From Ecoinvent database, copper sulphate ($CuSO_4$) has the most impact potential in terms of human toxicity based on the same quantity among all chemicals used in this study.

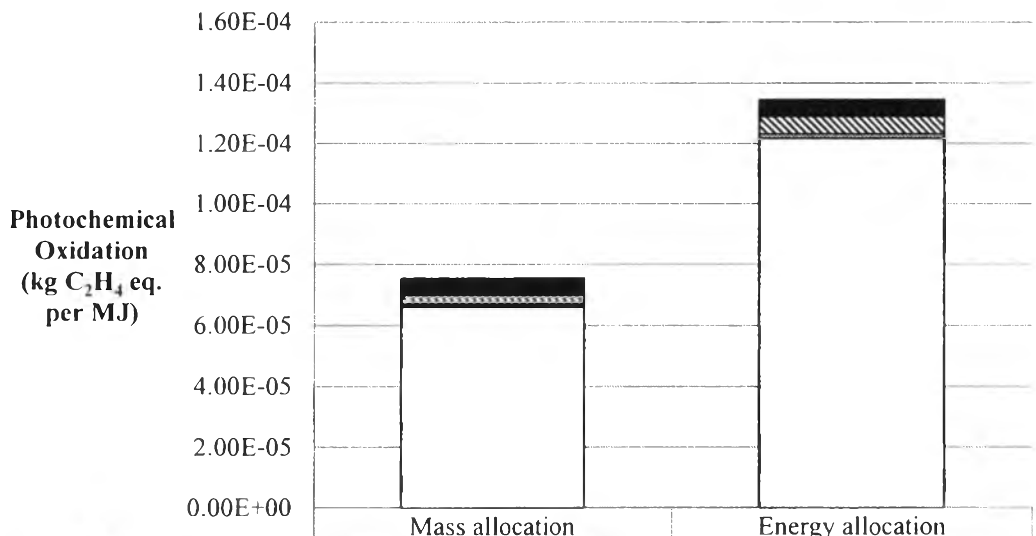


	Mass allocation	Energy allocation
■ Transesterification	4.105E-04	4.260E-04
▧ Oil Extraction	3.293E-05	6.060E-05
▩ Harvesting	7.408E-04	1.363E-03
□ Cultivation	4.977E-02	9.160E-02

Figure 4.14 Human toxicity potential based on 1 MJ biodiesel.

4.3.5 Photochemical Oxidation

Photochemical oxidation comes primarily from volatile organic compound that is released during the production of biodiesel. Volatile organic compounds (VOCs), carbon monoxide (CO), and methane (CH_4) are considered as the main contributor to photochemical oxidation. The potential value is expressed in terms of kilogram equivalent of ethylene (C_2H_4). Fig. 4.15 shows the results of photochemical oxidation impact on each process in the life cycle. Net photochemical oxidation potential contributed by microalgae-to-biodiesel process was found to be 7.551E-05 and 1.346E-04 kg C_2H_4 eq. per MJ biodiesel for mass allocation and energy allocation, respectively. The main contribution of this impact is a large amount of CO and CH_4 emitted from electricity generation.

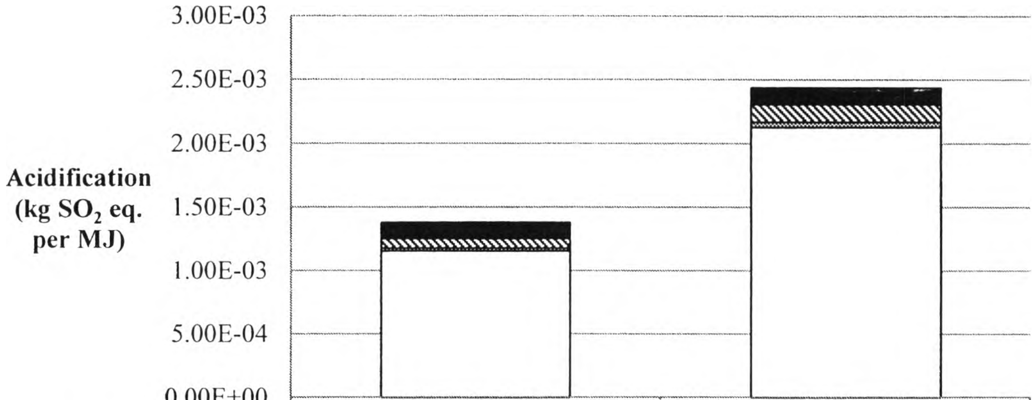


	Mass allocation	Energy allocation
■ Transesterification	5.440E-06	5.645E-06
▧ Oil Extraction	3.111E-06	5.726E-06
▩ Harvesting	8.270E-07	1.522E-06
□ Cultivation	6.613E-05	1.217E-04

Figure 4.15 Photochemical oxidation potential based on 1 MJ biodiesel.

4.3.6 Acidification

Acidification is caused by acid deposition which originates from emission of three main acidic substances: sulphur dioxides (SOx), nitrogen oxides (NOx), and ammonia (NH_3). Other organic and inorganic acids can also contribute to the acidification and increase the acidity of water, soil, and air. Sulphur dioxide (SO_2) is chosen as a reference acidic gas, and the impact of other emissions is computed by means of equivalency factors based on relative acidity, expressed as kilogram equivalent of SO_2. Fig. 4.16 shows the results of acidification impact on each process in the life cycle. Net acidification potential contributed by microalgae-to-biodiesel process was found to be 1.380E-03 and 2.437E-03 kg SO_2 eq. per MJ biodiesel for mass allocation and energy allocation, respectively. In this study, the main contribution of this impact comes from heat and electricity. Acidic gases, especially sulfur dioxide (SO_2) and nitrogen oxides (NOx), were released during the burning of coal and natural gas. Weigard (2001) also indicated that N_2O is produced naturally through fossil fuel combustion for energy production and transport.

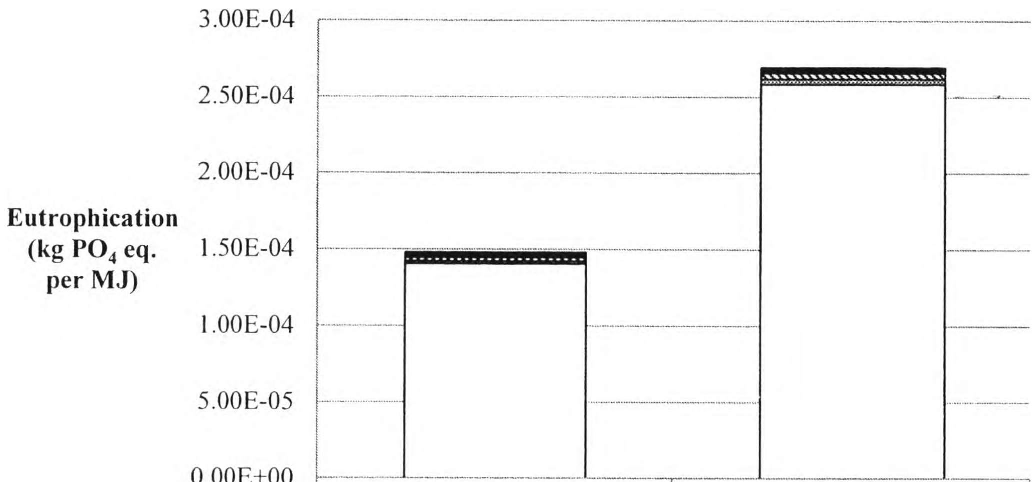


	Mass allocation	Energy allocation
■ Transesterification	1.287E-04	1.336E-04
Oil Extraction	7.396E-05	1.361E-04
Harvesting	2.153E-05	3.963E-05
□ Cultivation	1.156E-03	2.128E-03

Figure 4.16 Acidification potential based on 1 MJ biodiesel.

4.3.7 Eutrophication

Eutrophication refers to the effect of releasing excessive amount of nutrients, especially nitrate and phosphate. The contribution in this impact category is expressed in terms of kilogram equivalent of phosphate (PO_4). Both direct and indirect contributions were included in this study. Direct contribution was computed based on the quantity of emission that came from each production stage. Indirect contribution occurred from upstream processes, for example, chemicals production, electricity generation, etc. Fig. 4.17 shows the results of eutrophication impact on each process in the life cycle. Net eutrophication potential contributed by microalgae-to-biodiesel process was found to be 1.481E-04 and 2.696E-04 kg PO_4 eq. per MJ biodiesel for mass allocation and energy allocation, respectively. The main contribution of this impact is sodium nitrate ($NaNO_3$) which is one of the nutrients used in the cultivation process. Therefore, this impact could be reduced at least in proportion to the reduction of $NaNO_3$. However, this should be done with careful since decrease in $NaNO_3$ may have an adverse effect on the growth rate of microalgae. Quan (2006) studied the effects of sodium nitrate on the growth rate of microalgae *Nannochloropsis* and concluded that microalgae productivity increases when concentration of sodium nitrate increases.

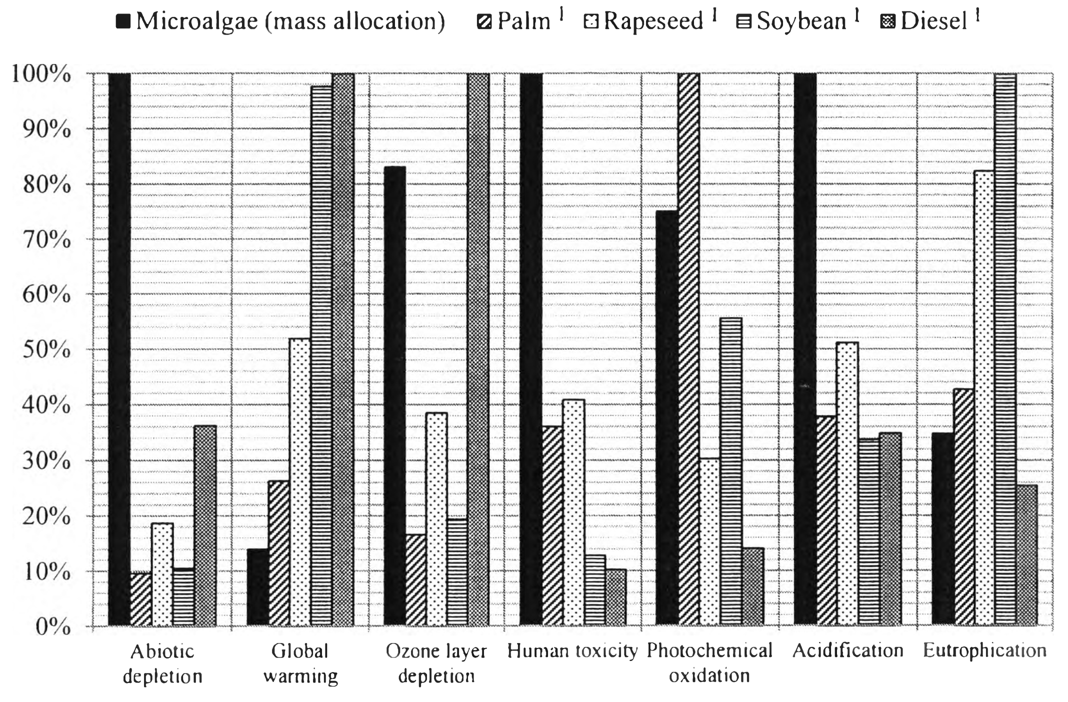


	Mass allocation	Energy allocation
■ Transesterification	3.627E-06	3.764E-06
Oil Extraction	2.054E-06	3.780E-06
Harvesting	1.919E-06	3.531E-06
□ Cultivation	1.405E-04	2.585E-04

Figure 4.17 Eutrophication potential based on 1 MJ biodiesel.

4.3.8 <u>Comparison</u>

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 (i.e. palm methyl ester, rapeseed methyl ester, and soybean methyl ester). 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 Fig. 4.18. All impact categories were standardized with the value of the worst scenario of each impact in order to identify its potential. Therefore, maximum value for each category is 100 %. 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.



[1] Lardon *et al.* (2009)

Figure 4.18 Comparison of environmental impacts based on 1 MJ biodiesel.

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 strong demand of hexane regarding to oil extraction leads to high photochemical oxidation potential compared to other biofuels. 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 during the cultivation process in which microalgae can fix up to 25 % of net greenhouse gas emissions (kg CO_2 equivalent). The allocation of co-product 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 also observed in other impact categories.

4.4 Improvement of Energy Consumption and Environmental Performance

4.4.1 Improvement of Energy Consumption

As shown in Fig. 4.9, it can be seen that cultivation process is the most energy consumed process. For mass allocation and energy allocation, the cultivation process consumes 84.23 % and 87.33 % of the total energy, respectively. According to a large amount of energy, the energy efficiency can be improved by selecting an appropriate method to enhance biomass production which would result in smaller amount of energy consumption per unit biomass produced. Consequently, NER can be expected to increase. In addition, changing type of microalgae could lead to a significant improvement of energy efficiency. This is due to different lipid content in different microalgae species. If lipid content of microalgae is higher, NER would be raised to a higher value.

Type of bioreactor is another parameter influencing the performance of microalgae system for biofuel production. Jorquera *et al.* (2010) performed an analysis of the energy life cycle for biomass production using oil-rich microalgae *Nannochloropsis*sp. This is a comparative study among raceway pond, tubular, and flat-plate photobioreactor for algal cultivation. The net energy ratio (NER) for each process was calculated. The results showed that the use of horizontal tubular photobioreactor is not economically feasible (NER<1) while NER of both raceway pond and flat-plate photobioreactor is greater than 1 (NER>1) which is considered economically feasible for biomass cultivation. In fact, the tubular and flat-plate photobioreactor have higher volumetric and areal productivity compared to the raceway pond. This is due to their higher ratio of illumination area relative to cultivation volume. As a result, the final biomass concentration in the photobioreactor is also higher. However, the energy consumption for pumping which is required for mass transfer is too high for the tubular photobioreactor. That is why the tubular photobioreactor is not economically feasible (NER<1). Therefore, the pumping energy should be reduced in order to raise NER as much as possible. In other words, productivity and energy consumption during the cultivation process should be compromised in order to arrive at appropriate conditions for biomass production.

Lastly, NER could be enhanced by improving production efficiency and co-products utilization. As oil extraction process usually generates a large amount of residue, the biogas produced from residue could be utilized for energy production which can compensate the energy usage. Collet *et al.* (2011) recently performed an LCA of biogas production from microalgae *Chlorella vulgaris*. Anaerobic digestion of raw microalgae was carried out in order to produce methane. They also suggested that the process should be combined with lipid recovery for a fraction of biomass. Thus, methane can be produced from both raw biomass and the remaining biomass after lipid extraction.

4.4.2 Improvement of Environmental Performance

According to impact assessment results, most of the impacts of microalgae-based biodiesel are directly related to the electricity consumption. Thus, it is clear that any reduction of the electricity consumption will result in a major reduction of the total environmental impact. As a result of improving net energy ratio (NER), the environmental impact of the whole system should be decreased as well. Furthermore, the nutrient requirement might be reduced by using wastewater emitted from the harvesting process as feed during the cultivation process. In a study by Soratana and Landis (2011), they also concluded that the utilization of resources from waste streams greatly helped reduce global warming potential (GWP) and eutrophication impact.

4.5 Sensitivity Analysis

As discussed in Section 4.4, several approaches could be done in order to improve the net energy ratio (NER) of microalgae-to-biodiesel process. Thus, in this section, sensitivity analysis was performed by using 4 important parameters: 1) biomass concentration, 2) lipid content, 3) energy consumption and 4) nutrient loading. These relevant parameters were varied in a reasonable range. The LCIA was performed and the results were compared to the base case scenario in order to gain a better understanding in how these parameters affect the performance of the microalgae-based biofuel production system.

4.5.1 Biomass Concentration

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 in this section. Fig. 4.19 and Fig. 4.20 show the net energy ratio (NER) and global warming potential (GWP), respectively, for the biomass concentration of microalgae ranging from 0.5 g/L to 4 g/L.

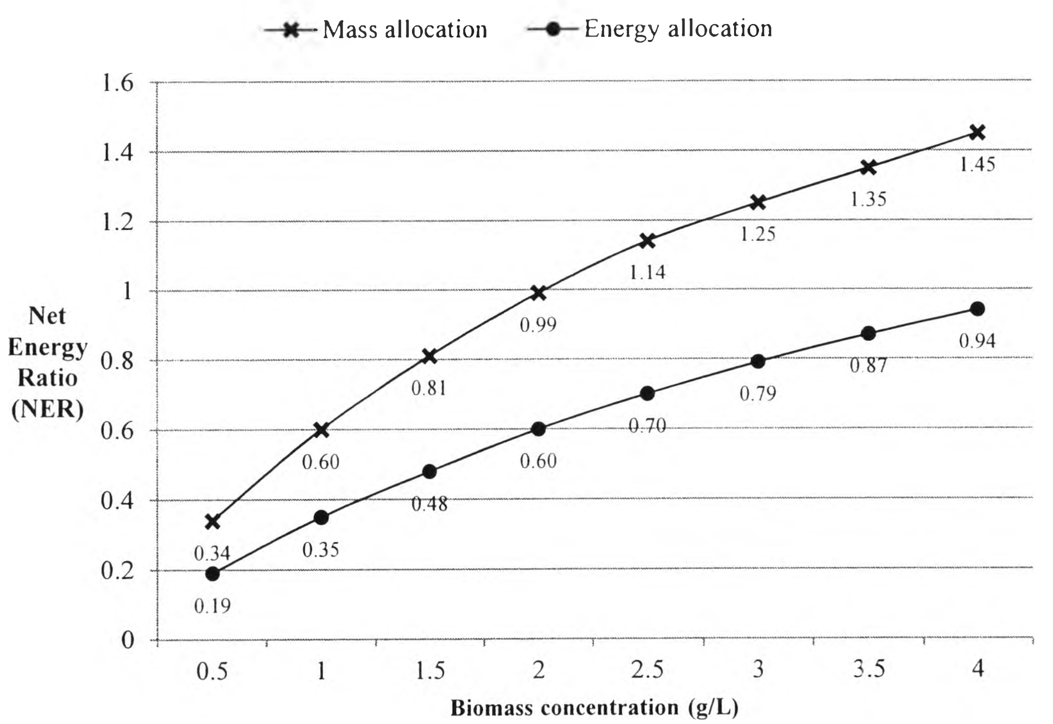


Figure 4.19 Sensitivity analysis of biomass concentration in terms of net energy ratio (NER).

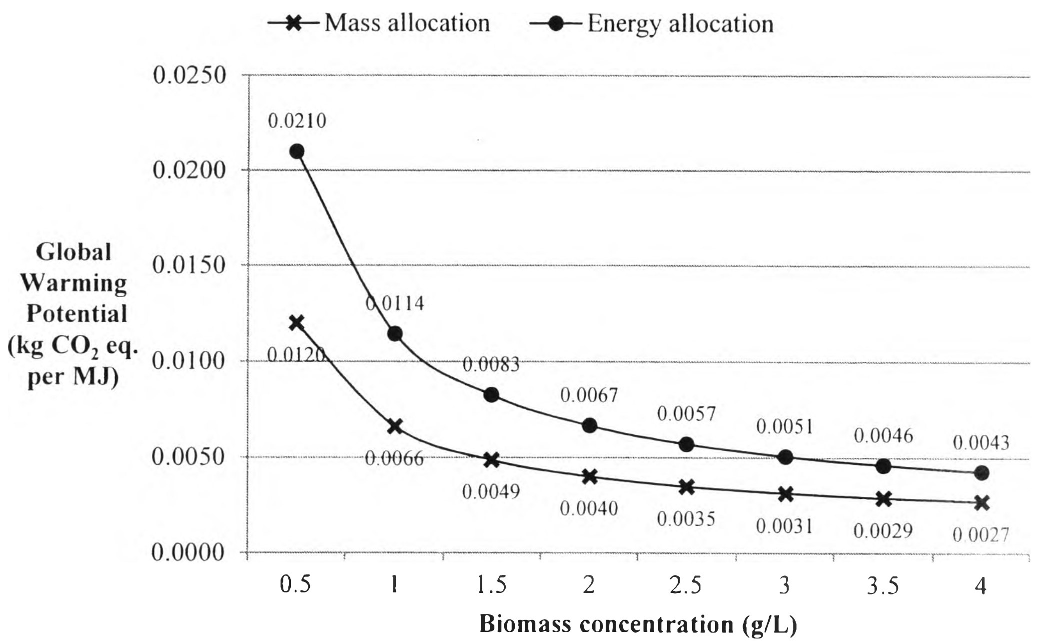


Figure 4.20 Sensitivity analysis of biomass concentration in terms of global warming potential (GWP).

It can be obviously seen from these two figures 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 Fig. 4.20.

4.5.2 Lipid Content

According to Chisti (2007), lipid content in microalgae was found to be in the range between 15 % and 80 % by weight. In this study, freshwater green microalgae *Scenedesmus armatus* contains a lipid content of 40 % by weight. Therefore, in this part of the study, the lipid content of the microalgae was increased from 40 % to 80 % by weight and the results are shown in Fig. 4.21 and Fig. 4.22 in terms of net energy ratio (NER) and global warming potential (GWP), respectively.

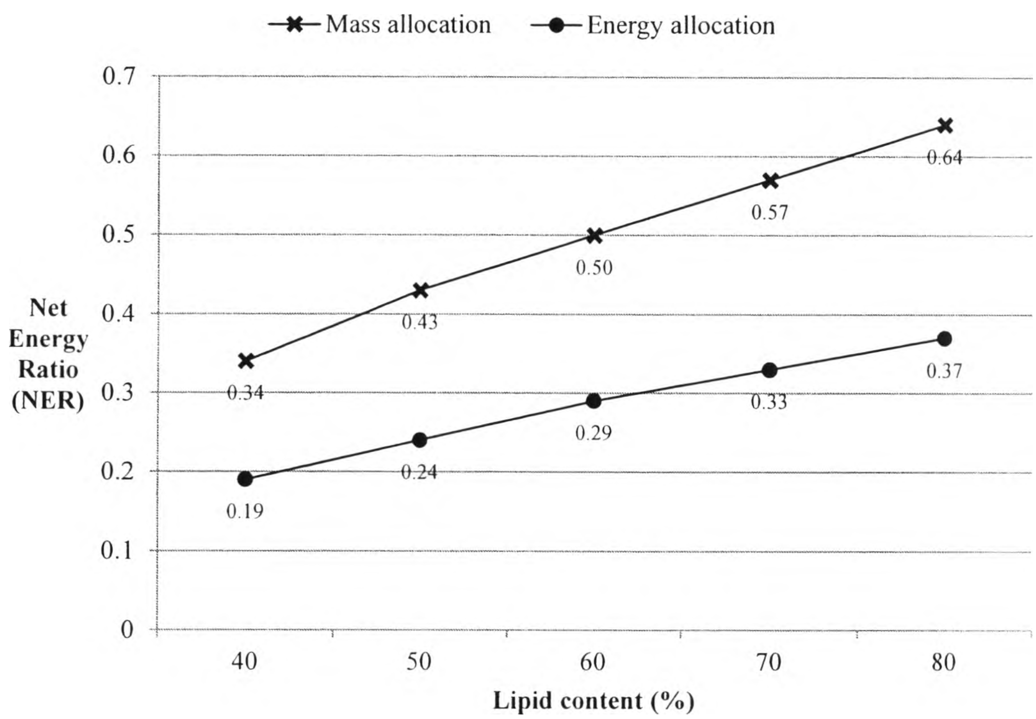


Figure 4.21 Sensitivity analysis of lipid content in terms of net energy ratio (NER).

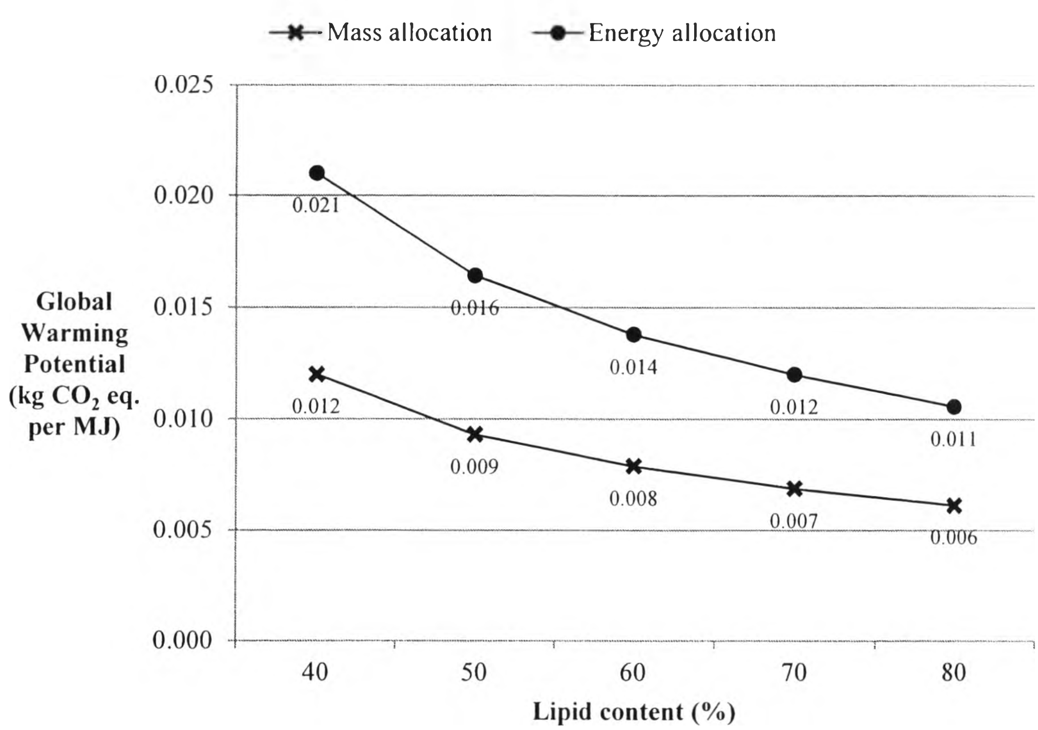


Figure 4.22 Sensitivity analysis of lipid content in terms of global warming potential (GWP).

It can be seen from Fig. 4.21 and 4.22 that lipid content of microalgae also has an effect on both the net energy ratio (NER) and global warming potential (GWP), but not as strongly as biomass concentration. When lipid content was increased from 40 % to 80 %, the net energy ratio (NER) increases almost double, but still cannot reach the value of 1 in any allocation methods. Fig. 4.22 also shows that global warming potential (GWP) decreases upon increasing the lipid content for both allocation methods.

4.5.3 Energy Requirement for Cultivation

From the previous section, the life cycle energy analysis reveals that the cultivation is the most energy consumed process in biodiesel production from microalgae which results mainly from electricity required for lighting and air pumping. Therefore, reduction in the energy consumption during the cultivation should result in better energy and environmental performance. The energy reduction based on the calculation in Appendix C is proposed for the sensitivity analysis as shown in Fig. 4.23 and Fig. 4.24.

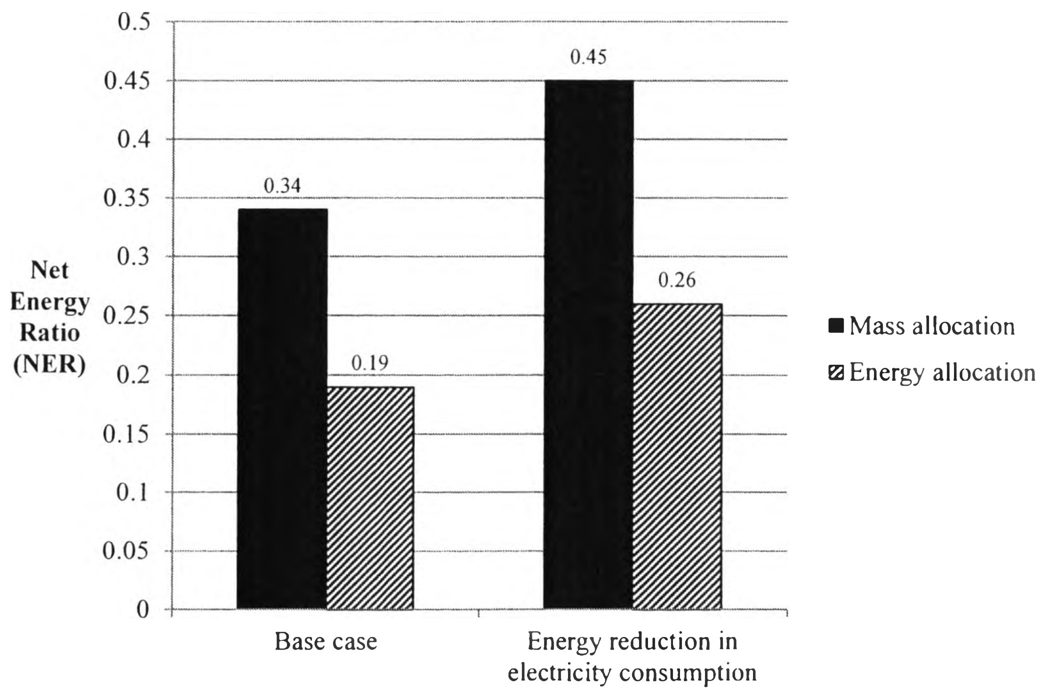


Figure 4.23 Sensitivity analysis of energy reduction in electricity consumption for cultivation in terms of net energy ratio (NER).

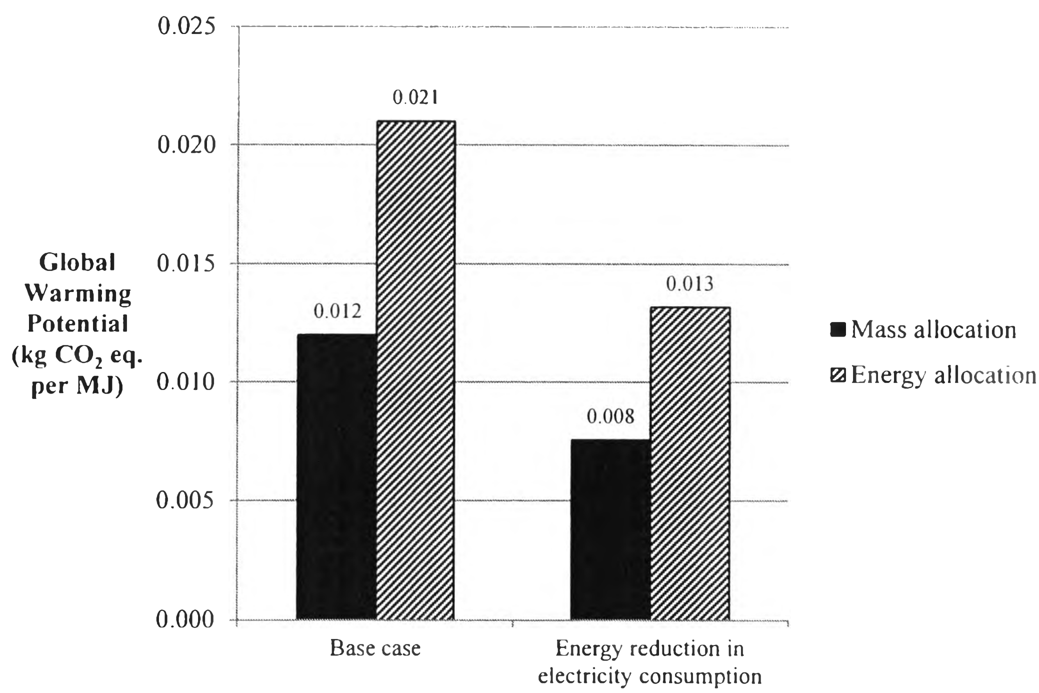


Figure 4.24 Sensitivity analysis of energy reduction in electricity consumption for cultivation in terms of global warming potential (GWP).

Based on this calculation, the energy consumption is reduced by 97.5 % and 49.8 % for lighting and air pumping, respectively. The results from sensitivity analysis in Fig.4.23 and Fig.4.24 show that the net energy ratio (NER) increases around 35 % while the global warming potential (GWP) decreases around 36 % for both allocation methods.

4.5.4 Nutrient Loading

According to the life cycle energy analysis, cultivation is the process that consumes most energy and the majority of the energy consumed in this process comes from the energy used in the production of chemicals which are used as nutrients. Consequently, reduction in chemicals usage in the cultivation process would lead to the reduction of overall energy consumption. Therefore, the reduction in chemicals used is being proposed as the last parameter in the sensitivity analysis. A cut off of 0.2 % for chemicals usage is chosen for this study which means that all materials which contribute less than 0.2 % in terms of mass with respect to the total weight are excluded in the process. As a result, this cut off ratio excludes all trace metal solution (i.e., H_3BO_3, $MnCl_2 \cdot 4H_2O$, $ZnSO_4 \cdot 7H_2O$, $Na_2MoO_4 \cdot 2H_2O$, $CuSO_4 \cdot 5H_2O$, and $Co(NO_3)_2 \cdot 6H_2O$) and $EDTANa_2$. The results are shown in Fig. 4.25 and Fig. 4.26.

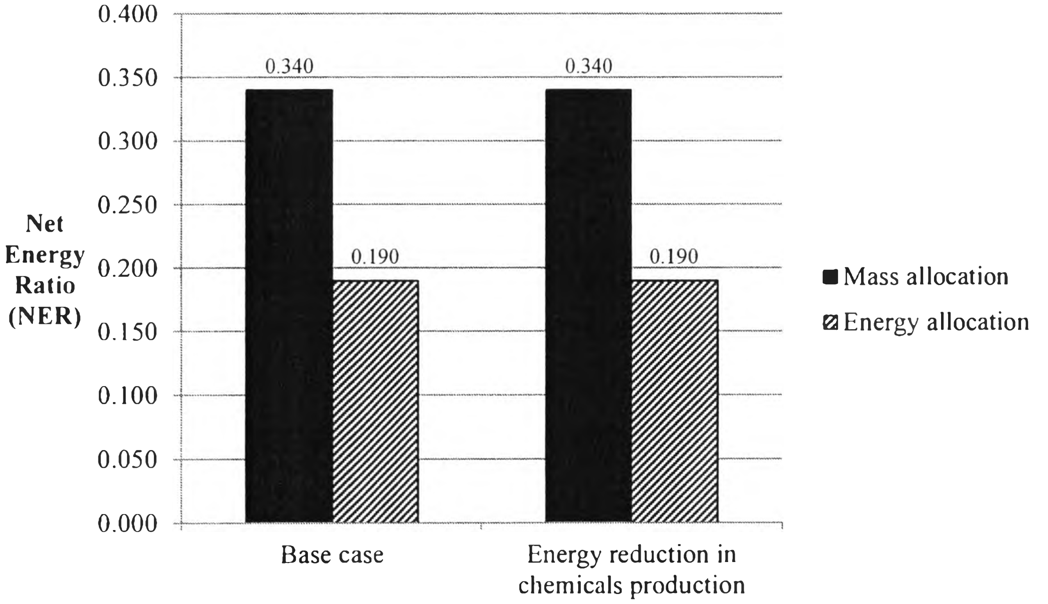


Figure 4.25 Sensitivity analysis of energy reduction in chemicals production for cultivation in terms of net energy ratio (NER).

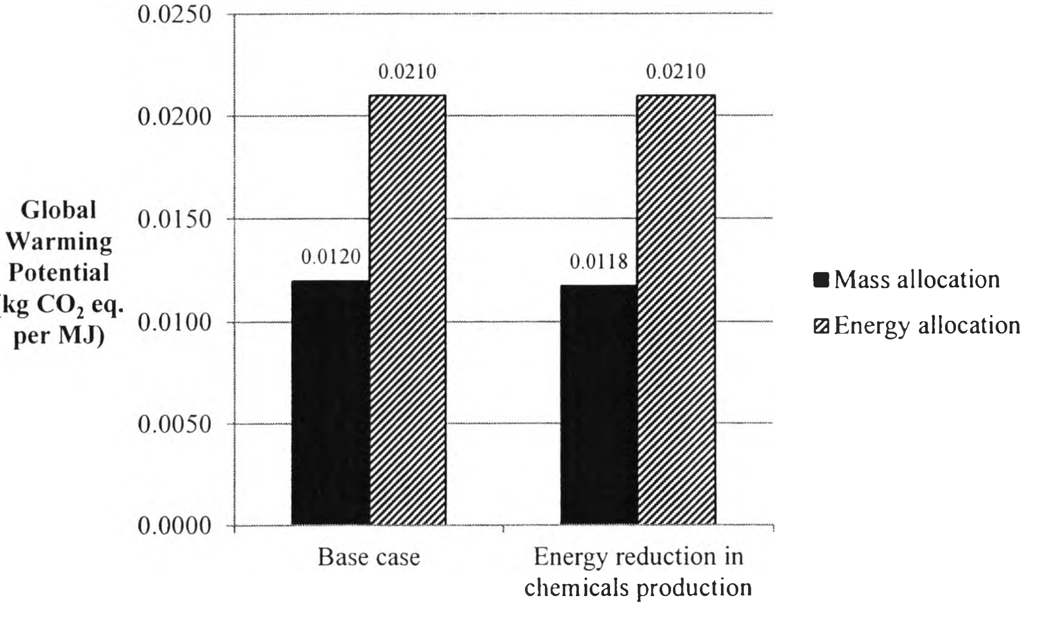


Figure 4.26 Sensitivity analysis of energy reduction in chemicals production for cultivation in terms of global warming potential (GWP).

The results show that the reduction in chemicals usage by excluding of some materials do not have a significant effect on both net energy ratio (NER) and global warming potential (GWP). Additionally, sodium nitrate ($NaNO_3$) becomes a main contributor in terms of energy consumption and environmental impact in the cultivation process. Therefore, the reduction of $NaNO_3$ could be improved NER and GWP. However, as stated earlier, this should be done with careful since decrease in $NaNO_3$ may have an adverse effect on the growth rate of microalgae. Quan (2006) studied the effects of sodium nitrate on the growth rate of microalgae *Nannochloropsis* and concluded that microalgae productivity increases when concentration of sodium nitrate increases.