CHAPTER IV
RESULTS AND DISCUSSION

4.1 Life Cycle Inventory (LCI)

The life cycle inventory data were collected from secondary data sources (National Thai LCI database, previous works on LCA of palm oil based microemulsion biofuel, and selected references) based on the functional unit (one ton) of microemulsion biofuel production and the boundary of biofuel production. In this study, the boundary of ME biofuel production consists of four stages: cultivation, oil extraction, refining and microemulsion production. In microemulsion biofuel production stage, four different formulations such as scenario I, II, III and IV have been assessed and compared.

4.1.1. Cultivation

Oil palm normally takes two and a half to three years to start bearing bunches and continues bearing until the end of its lifetime, approximately 25 years. It yields about 3.6 tons of fresh fruit bunch (FFB) per rai per year (23 tons of FFB per hectare per year). The oil palms are planted with the density ranging from 128 to 148 trees per hectare, depending on the planting material, soil and climate (Papong *et al.*, 2009). The fertilizers used are 7.79 kg/ton FFB for N fertilizer from ammonium sulphate , 0.05 kg/ton of FFB for P_2O_5 fertilizer from ground rock phosphate and 14.41 kg/ton FFB for K_2O fertilizer from potassium chloride . Moreover, 0.28kg/ ton of FFB and 0.10kg/ton FFB of glyphosate and paraquat respectively are used as herbicide at an average of 1-3 times per year.They are used every year, but the rates of application are different depending on the age of the plants. The usual frequency of a harvesting round of FFB is 10-15 days or 2-3 times a month. Water requirement for the oil palm plantation is mostly from rain water since most of the plantations are located in the tropical region.Young palms are harvested with a chisel whereas old and tall palms are harvested with a long-handled sickle. As they are harvested only by manual labor, there is no fossil energy input to harvesting. In this study, the representative oil palm plantation and crude palm oil mill are located in the Krabi

province, in the southern part of Thailand. The palm oil mill is located close to the palm field; it is 34 km for round trip with 3-ton truck in the assumption. The fuel consumption for the heavy diesel vehicles used for transportation of FFB was 1.6 km/L of diesel (Pleanjai, 2009).

Table 4.1 Inventory data for cultivation stage (base case)

Input		References
N- fertilizer(kg)	21.26	Pleanjai, 2009
P_2O_5 -fertilizer(kg)	0.14	Pleanjai , 2009
K_2O-fertilizer (kg)	39.34	Pleanjai , 2009
Glyphosate (kg)	0.75	Pleanjai , 2009
Paraquate (kg)*	0.27	Pleanjai , 2009
Diesel used (for transport FFB) (kg)	18.12	Pleanjai , 2009
Output		
Product FFB (kg)	2726.13	Pleanjai , 2009

*Bipyridylium has been substituted in the calculation.

4.1.2 Extraction

Typically, the fresh fruit bunches (FFB) are directly transported to palm oil mills and extracted within 24 hours to ensure the desired quality. The outputs from palm oil mill include crude palm oil (15-18 %), shells (5-6%), kernels (5-6%), palm fiber (12-14%), and empty fruit bunches (25-27%) (Papong, 2009). The primary product is crude palm oil (CPO) which is approximately 0.163 ton/ ton FFB (PleanjaiS., 2009).Fiber residues and empty fruit bunches (EFB) are used as a biomass fuel to generate internal power in the form of heat and electricity, which are integrated to the palm oil mill. Diesel oil used in the production process is approximately 1.62 liter /ton FFB which is used for the diesel generator and other

diesel machines in the plant. In addition, palm oil mill effluent (POME) contains high COD loading (above 100,000 mg/L) (Kaewmai, 2012).

Table 4.2 Inventory data for extraction stage (base case)

Input		References
FFB(kg)	2726.13	Pleanjai, 2009
Water(completely softerned at plant)(kg)	2269.93	Kaewmai, 2012
Diesel for machine (low sulphur,at refinery)(kg)	1.08	Kaewmai, 2012
Electricity from grid (kWh)	6.96	Kaewmai, 2012
Output		
Product		
CPO(kg)	444.36	Pleanjai, 2009
Co-product		
Palm kernel(kg)	142.08	Kaewmai, 2012
Solid waste		
EFB(kg)	581.64	Kaewmai, 2012
Decanter cake(kg)	93.24	Kaewmai, 2012
Fiber(kg)	168.72	Kaewmai, 2012
Shell(kg)	159.84	Kaewmai, 2012
Liquid waste		
Palm oil mill effluent (m^3)	1.52	Kaewmai, 2012

4.1.3 Refining

In crude palm oil refining process, main product is palm olein and the co-product is palm stearin. The neat palm oil yield is 0.71 kg/kg of crude palm oil (CPO) and palm stearin yield is 0.29 kg/kg CPO (Papong *et al.*, 2009). As an assumption, microemulsion biofuel production is carried out near the palm oil mill.

Table 4.3 Inventory data for refining stage (base case)

Input		Reference
CPO (kg)	444.36	Arpornpong, 2013
Water (kg)	52.58	Arpornpong, 2013
Phosphoric acid (85% in H_2O) (kg)	0.41	Arpornpong, 2013
Bentonite (kg)	4.14	Arpornpong, 2013
Electricity from grid (kWh)	369.1	Arpornpong, 2013
Output		
Product		
palm olein (kg)	315.5	Papong *et al.*, 2009
Co-product		
palm stearin (kg)	128.86	Papong *et al.*, 2009

4.1.4 Microemulsion

According to the previous study (Arpornpong, 2013), major environmental impact is mainly contributed from raw materials selection at micromemulsion production stage. Because of the fact that different ME formulasions (Scenario I, II, III and IV) have been analyzed and compared.

4.1.4.1 Scenario I (Base Case)

Formulation of microemulsion-based biofuel (ME50) was the mixture of methyl oleate /1-octanol (22 vol. %), ethanol (20 vol. %), and the palm oil/diesel blend (58 vol. %). Methyl oleate and 1-octanol were used as nonionic surfactant and cosurfactant, respectively. Ethanol was used as polar phase In this study, palm olein was employed to formulate microemulsion fuels. Materials applied in the microemulsion biofuel production were the palm olein/diesel (1:1) by volume, ethanol and methyl oleate/1-octanol (1:8) by molar (Arpornpong *et al.*, 2014). Palm olein (0.321 ton/ton of ME50) and diesel (0.289ton/ton of ME50) were directly mixed for ME biofuel production. Electrical energy consumption required for the mixing process only was approximately 7.46 kWh/ton of ME50. Particularly, biofuel

microemulsion contributes ME50 with an absolute 100 percent yield without any waste or byproduct generation during the microemulsification (Arpornpong, 2013).

Table 4.4 Inventory data for Scenario I (Base Case)

Input		References
Palm olein(kg)	315.5	Arpornpong, 2013
Ethanol from ethylene(kg)	184.6	Arpornpong, 2013
Surfactant(kg)*	75.2	Arpornpong, 2013
Cosurfactant (kg)**	139.6	Arpornpong, 2013
Diesel, low sulphur, at refinery(kg)	285	Arpornpong, 2013
Electricity thailand base 2007 (kWh)	7.46	Arpornpong, 2013
Output		
Product		
Microemulsion biofuel (ton)	1	Arpornpong, 2013

*Ethoxylated alcohol has been substituted in the calculation

**1-butanol has been substituted in the calculation

4.1.4.2 Scenario II (Biobased Case)

In Scenario II, formulation of ME was conducted from renewable based component. Biobased case was simulated by fatty acid methyl ester (FAME) and bioethanol produced from biomass substituting instead of methyl oleate and ethanol produced from pectrochemical process. Composition of microemulsion fuel are surfactant/cosurfactant blend (1:8) by molar, vegetable oil/diesel mixture (1:1) by volume and ethanol. Palm olein (0.301 ton/ton of ME biofuel) and diesel (0.284ton/ton of ME biofuel) were directly mixed for ME biofuel production. Electrical energy consumption required for the mixing process only was approximately 7.46 kWh/ton of ME biofuel.This inventory data were collected from laboratory research (Manaphati, 2015).

Table 4.5 Inventory data for Scenario II

Input		Reference
Palm olein(kg)	305.54	Manaphati, 2015
Bioethanol (kg) •	189.76	Manaphati, 2015
Palm methyl ester(kg)	47.11	Manaphati, 2015
1-octanol,propylene hydroformylation(kg)*	168.89	Manaphati, 2015
Diesel, low sulphur (kg)	288.7	Manaphati, 2015
Electricity thailand base 2007 (kWh)	7.46	Arpornpong, 2013
Output		
Product		
Microemulsion biofuel (ton)	1	

*1-butanol has been substituted in the calculation

4.1.4.3 Scenario III (Butanol Blend Case)

Formulation of Scenario III was the blending of butanol and ethanol as polar phase. Based on Arpornpong and coworkers' study (2013), the key factor which contributes to environmental impacts of ME came from raw materials including surfactant and cosurfactant. In this study, microemulsion biofuel with buthanol blend could reduce the amount of surfactant used in ME formulation. Composition of microemulsion fuel were surfactant/cosurfactant blend (1:8) by molar, vegetable oil/diesel mixture (3:7) by volume and ethanol/butanol blend (9:1) by molar. Palm olein (0.183 ton/ton of ME biofuel) and diesel (0.404 ton/ton of ME biofuel) were directly mixed for ME biofuel production. Electrical energy consumption required for the mixing process only was approximately 7.46 kWh/ton of ME biofuel.This inventory data were collected from laboratory research (Apichatyothin, 2015).

Table 4.6 Inventory data for Scenario III

Input		References
Palm olein(kg)	186.3	Apichatyothin, 2015
Ethanol from ethylene (kg)	171.92	Apichatyothin, 2015
Methyl oleate*(kg)	60.84	Apichatyothin, 2015
1-octanol(kg)**	150.93	Apichatyothin, 2015
Diesel, low sulphur (kg)	410.93	Apichatyothin, 2015
1-butanol, propylene hydroformaltion(kg)	19.08	Apichatyothin, 2015
Electricity thailand base 2007 (kWh)	7.46	Arpornpong, 2013
Output		
Product		
Microemulsion biofuel (ton)	1	

*Ethoxylated alcohol has been substituted in the calculation

**1-butanol has been substituted in the calculation

4.1.4.4 Scenario IV (RDBPO Case)

In Scenario IV, refined deodorized and bleached palm oil (RDBPO) was applied instead of refined palm oil. In order to reduce the emissions from palm oil production, scenario IV was simulated by bypassing the step of oil refinery In refining stage, distillation process which is used to separate palm olein and palm stearin required extensive energy. Composition of microemulsion fuel are surfactant/cosurfactant blend (1:8) by molar, RDBPO/diesel mixture (1:1) by volume and ethanol. RDBPO (0.319 ton/ton of ME biofuel) and diesel (0.296 ton/ton of ME biofuel) were directly mixed for ME biofuel production. Electrical energy consumption required for the mixing process only was approximately 7.46 kWh/ton of ME biofuel.This inventory data were collected from laboratory research (Manaphati, 2015).

Table 4.7 Inventory data for Scenario IV

Input		References
RDBPO(kg)	324.68	Manaphati, 2015
Ethanol from ethylene(kg)	188.52	Manaphati, 2015
Methyl oleate(kg)*	53.19	Manaphati, 2015
1-octanol(kg)**	132.2	Manaphati, 2015
Diesel, low sulphur, at refinery(kg)	301.4	Manaphati, 2015
Electricity thailand base 2007 (kWh)	7.46	Arpornpong, 2013
Output		
Product		
Microemulsion biofuel (ton)	1	

RDBPO- Refined Deodorized Bleached Palm Oil

*Ethoxylated alcohol has been substituted in the calculation

**1-butanol has been substituted in the calculation

4.1.4.5 Comparison of the Properties of ME Biofuels

Comparison of the properties of ME biofuels and neat diesel are shown in Table 4.8.

Table 4.8 Comparison of the Properties of ME biofuels and neat diesel

Properties of ME biofuel	SI *	SII **	SIII ***	SIV **	Neat diesel ****
Density,kg/cm3 @ 20° C	0.85	0.85	-	0.87	0.83
Kinematic viscosity,cst @ 40° C	4	6	4	6	3
Heat of combustion,MJ/kg	39	39	39	39	50
Flash point (° C)	15	-	-	-	1
Cloud point (°C)	-	5	-3	5	-

* (Arpornpong, 2013)

** (Manaphati , 2015)

***(Apichatyothin , 2015)

****(Sivaramakrishnan , 2011)

4.2 Greenhouse Gas Emission

The total GHG emissions of the ME production for different scenarios described in the unit of CO_2-equivalent (CO_2eq) are illustrated in Fig. 4.1. Among them, scenario IV represents the lowest GHG emissions (1,017 $kgCO_2$) as a result of using RBDPO instead of palm olein in the ME formulation. When RBDPO was used to formulate ME biofuel, the total GHG emission was significantly reduced by 40 percent compared to base case (1,448 $kgCO_2$).
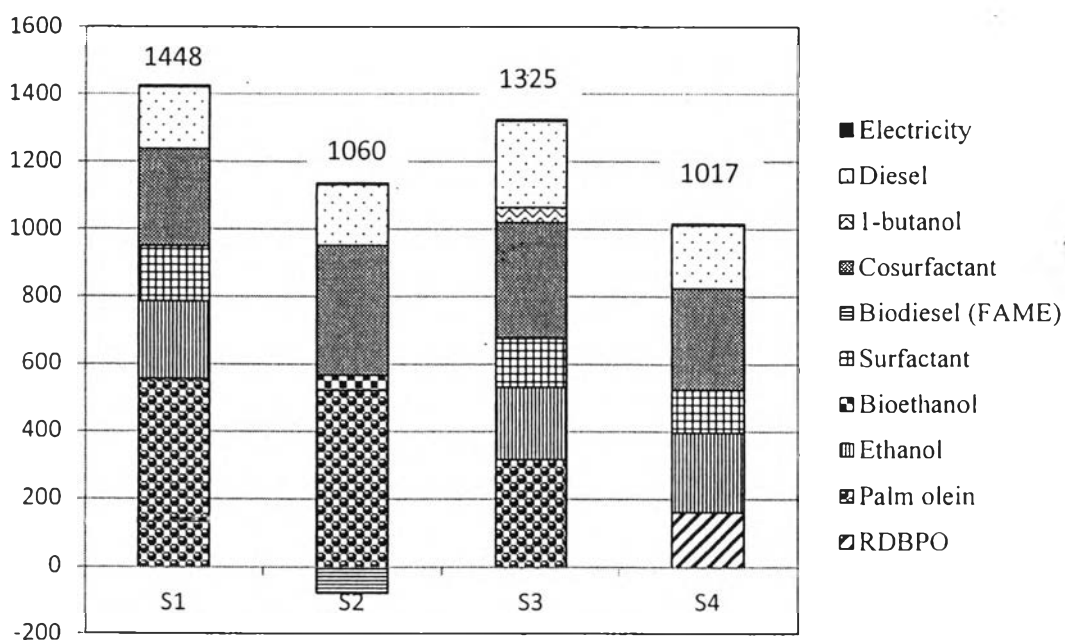
Figure 4.1 GHG emissions (kg of CO_2 eq.) per 39,000 MJ of ME biofuel.

Comparing GHG emissions of ME production process, it can be seen that the GHG emissions from raw material preparation accounted for 99% of all GHG emissions. In contrast, the production process accounted for only 1% in the case of electrical mixing. It can be noted that a GHG emission generated from production of palm olein was remarkably high relative to other raw materials. In palm olein production process, energy used in refining stage contributes more than other cultivation and extraction stages. In scenario IV, the GHG emissions of RBDPO production was lower than that of neat palm olein due to bypass the emissions from oil refining process which requires high energy supply.

According to the Fig. 4.2, palm olein production; especially from N fertilizer loading during cultivation, was the highest GHG emission potential about at Scenario I and Scenario II. Furthermore, cosurfactant used in formulation of Scenario III and IV significantly accounted about 30 percent of GHG emission. In addition, the reverse impact was observed in Scenario II (biobased case) when using biodiesel instead of surfactant. The result is mainly influenced by the biodiesel production process.
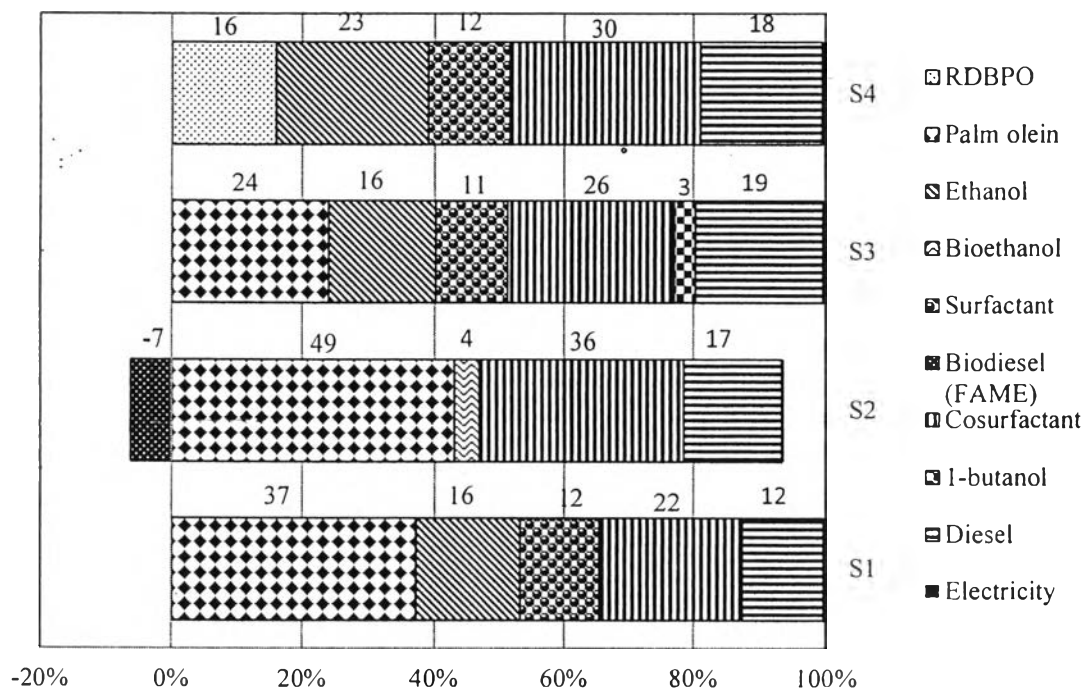
	16	23	12	30	18	
S4						
	24	16	11	26	3	19
S3						
-7	49	4	36	17		S2
	37	16	2	22	12	S1

-20% 0% 20% 40% 60% 80% 100%

☐ RDBPO
☐ Palm olein
☒ Ethanol
☑ Bioethanol
☒ Surfactant
☒ Biodiesel (FAME)
☐ Cosurfactant
☒ 1-butanol
☐ Diesel
■ Electricity

Figure 4.2 Comparison of the GHG emissions per 39,000 MJ of ME biofuels.

4.3 Life Cycle Impact Assessment (LCIA)

Environmental impacts of microemulsion biofuel production process were assessed by CML 2 baseline 2000 method. In this study, eleven potential environmental impact categories including acidification, eutrophication, abiotic depletion, greenhouse gas (GHG) emission, ozone layer depletion (ODP), human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, land use and photochemical oxidation were evaluated. Designated methodologies for microemulsion biofuel production process are shown in Table 4.9.

Table 4.9 Designated methodologies for microemulsion biofuel production life cycle assessment under SimaPro v. 7.1

Indicators	Methodology	Unit
Acidification	CML 2000	kg SO_2 eq.
Eutrophication	CML 2000	kg PO_4 eq
GWP 100a	CML 2000	kg CO_2 eq.
Terrestrial ecotoxicity	CML 2000	kg 1,4-DB eq
Human toxicity	CML 2000	kg 1,4-DB eq.
Fresh water aquatic ecotoxicity	CML 2000	kg 1,4-DB eq.
Marine aquatic ecotoxicity	CML 2000	kg 1,4-DB eq.
Ozone layer depletion	CML 2000	kg CFC-11 eq.
Abiotic depletion	CML 2000	kg Sb eq.
Photochemical oxidation	CML 2000	kg C_2H_4 eq.
Land use	Eco-indicator 99(H)	PDF m^2 yr.

4.3.1 Common Impacts Related to Microemulsion Biofuel Production

4.3.1.1 Global Warming Potential

The greenhouse gases considered in this study are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The greenhouse gas emission (GHG) is expressed in terms of kilogram equivalent of CO_2. (Wibul, 2012). According to the Fig. 4.3, the lowest GHG emission was observed from formulation of ME biofuel Scenario IV with RBDPO as a based vegetable oil instead of palm olein. In contrast, highest GHG emission formulation was Scenario I in which palm olein production contributed significant impact more than other materials used.
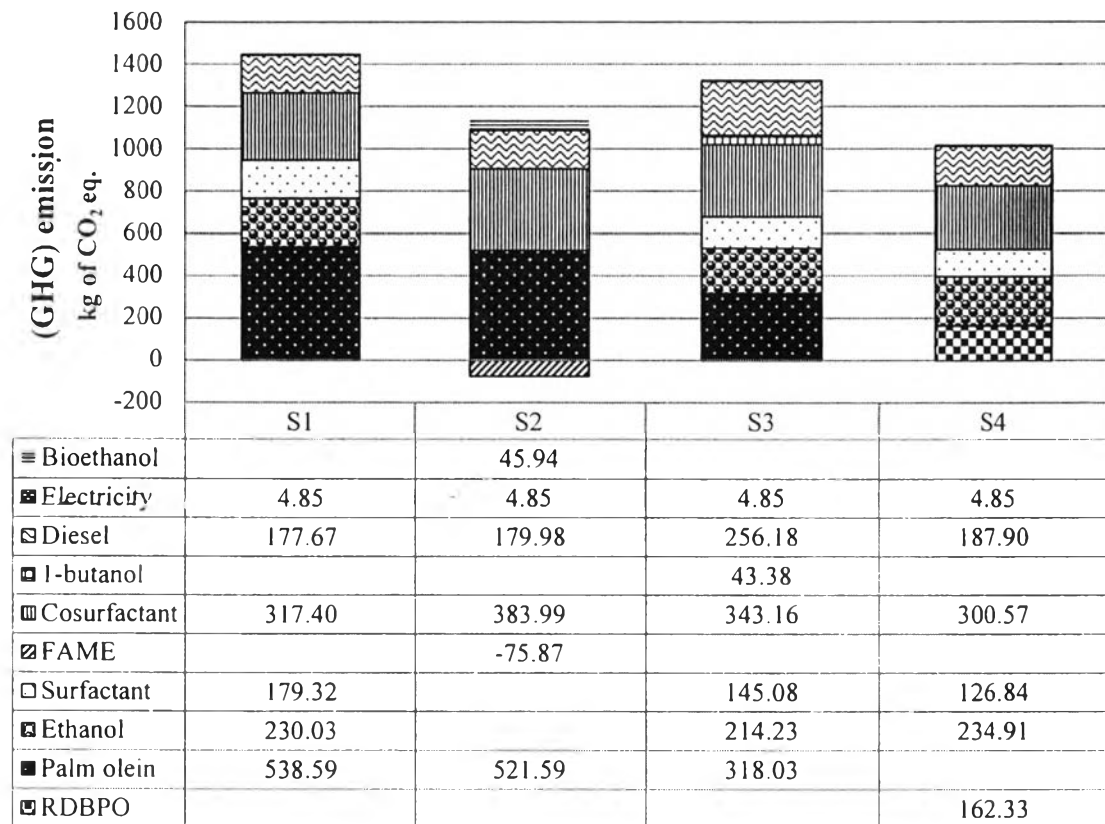
	S1	S2	S3	S4
≡ Bioethanol		45.94		
⊞ Electricity	4.85	4.85	4.85	4.85
⊠ Diesel	177.67	179.98	256.18	187.90
▣ 1-butanol			43.38	
▥ Cosurfactant	317.40	383.99	343.16	300.57
▨ FAME		-75.87		
☐ Surfactant	179.32		145.08	126.84
▤ Ethanol	230.03		214.23	234.91
■ Palm olein	538.59	521.59	318.03	
▦ RDBPO				162.33

Figure 4.3 Greenhouse Gas (GHG) emission based on 1 ton of ME biofuel.

4.3.1.2 Acidification

Acidification is caused by acid deposition which is occured from emission of three main acidic substances. They are sulphur oxides (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 is chosen as a reference acidic gas, and the impact of other emissions is also computed by means of equivalent factors based on relative acidity. Acidification potential is expressed as kilogram equivalent of SO_2. (Wibul, 2012) Fig. 4.4 shows the results of acidification impact from each ME formulation. Among them, Scenario II (biobase case) contributed the highest acidification impact from bioethanol production process.
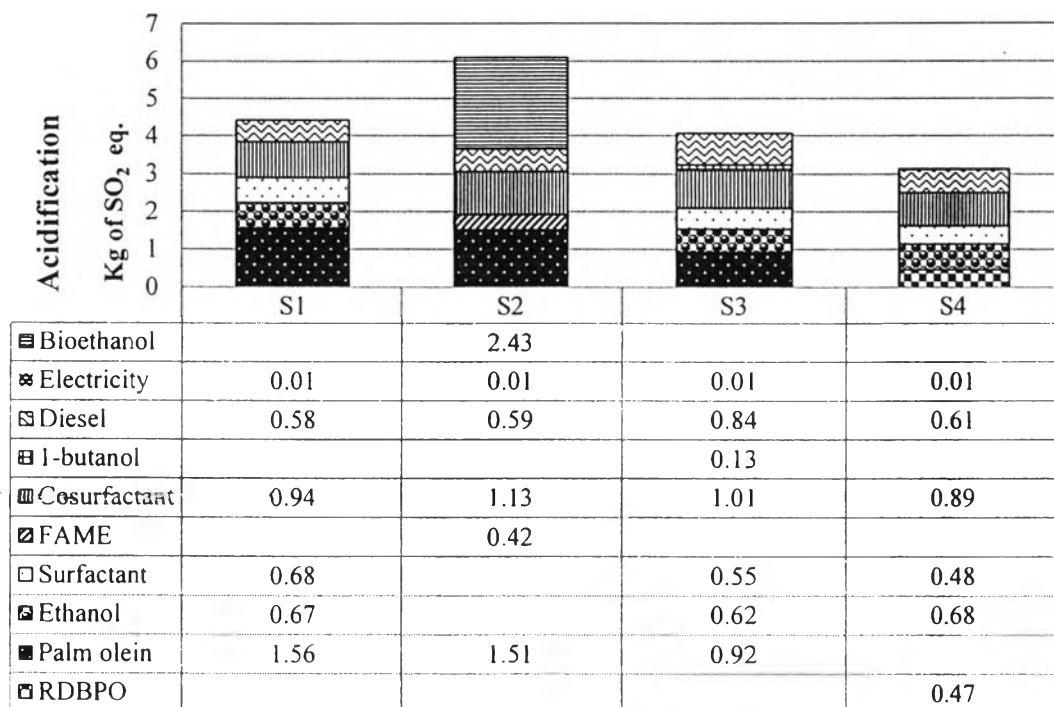
The figure shows a stacked bar chart with the following data table below it:

	S1	S2	S3	S4
⊟ Bioethanol		2.43		
⊠ Electricity	0.01	0.01	0.01	0.01
⊠ Diesel	0.58	0.59	0.84	0.61
⊞ 1-butanol			0.13	
⊞ Cosurfactant	0.94	1.13	1.01	0.89
⊠ FAME		0.42		
☐ Surfactant	0.68		0.55	0.48
⊠ Ethanol	0.67		0.62	0.68
■ Palm olein	1.56	1.51	0.92	
⊡ RDBPO				0.47

Figure 4.4 Acidification potential based on 1 ton of ME biofuel.

4.3.1.3 Abiotic Depletion

Abiotic depletion is an indicator for the depletion of non-renewable natural resources, including 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. Abiotic depletion is expressed as kilogram equivalent of Sb (Wibul, 2012) Fig. 4.5 shows the results of abiotic depletion impact from each ME formulation. Among them, Scenario III contributed the highest abiotic depletion impact on environment from the fact of high amount of diesel blend in the ME formulation. Application of fossil fuel is the main contributor of abiotic depletion.
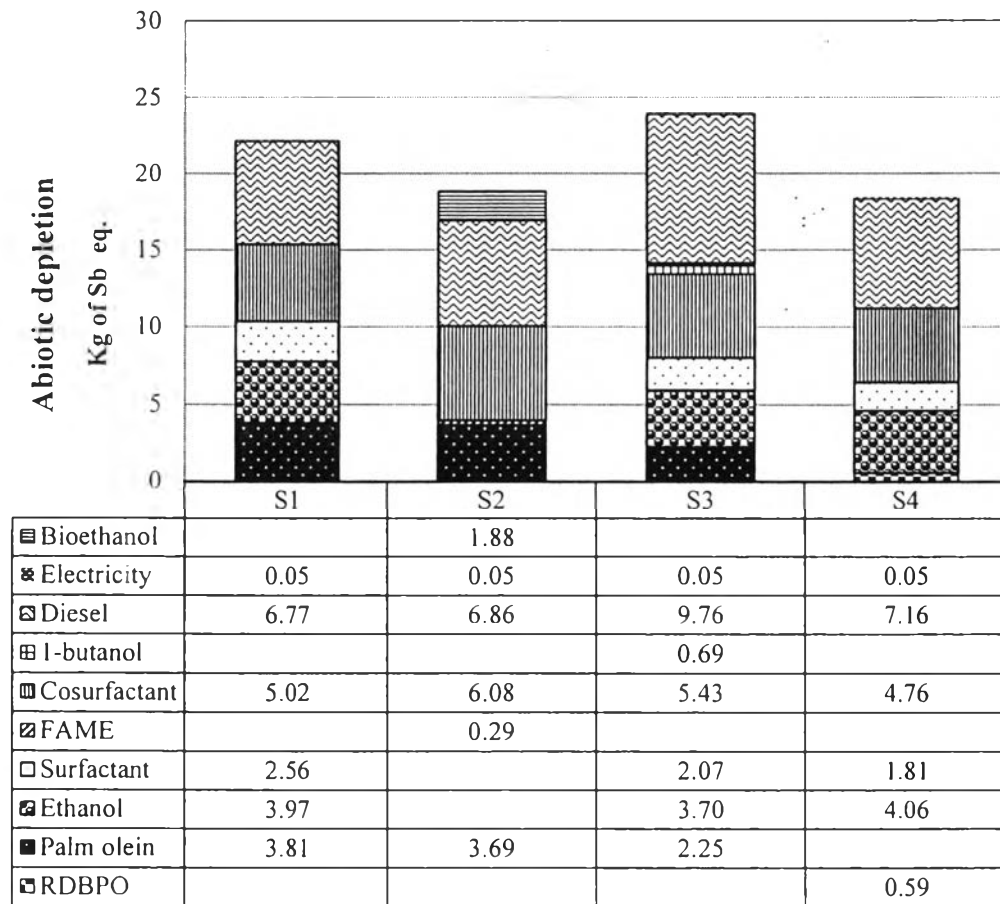
	S1	S2	S3	S4
⊟ Bioethanol		1.88		
✹ Electricity	0.05	0.05	0.05	0.05
◩ Diesel	6.77	6.86	9.76	7.16
⊞ 1-butanol			0.69	
▥ Cosurfactant	5.02	6.08	5.43	4.76
▨ FAME		0.29		
☐ Surfactant	2.56		2.07	1.81
▨ Ethanol	3.97		3.70	4.06
■ Palm olein	3.81	3.69	2.25	
◫ RDBPO				0.59

Figure 4.5 Abiotic depletion potential based on 1 ton of ME biofuel.

4.3.1.4 Ozone Layer Depletion

Ozone layer depletion is occurred by high level of chlorine and bromine compounds such as chlorofluorocarbons (CFCs), carbon tetrachloride (CCL_4), methyl bromide (CH_3Br), methyl chloroform (CH_3CCl_3), and halons (EPA 2010) in the stratosphere. The typical indicator for ozone layer depletion is chlorofluorocarbon (CFC). Ozone layer depletion potential of different gases is measured as kilogram equivalent of trichlorofluoromethane (CFC-11) (Wibul, 2012) Fig. 4.6 shows the results of ozone layer depletion impact from each ME formulation. Especially, diesel usage in all four scenarios contributed the significant ozone layer depletion impact on the environment.
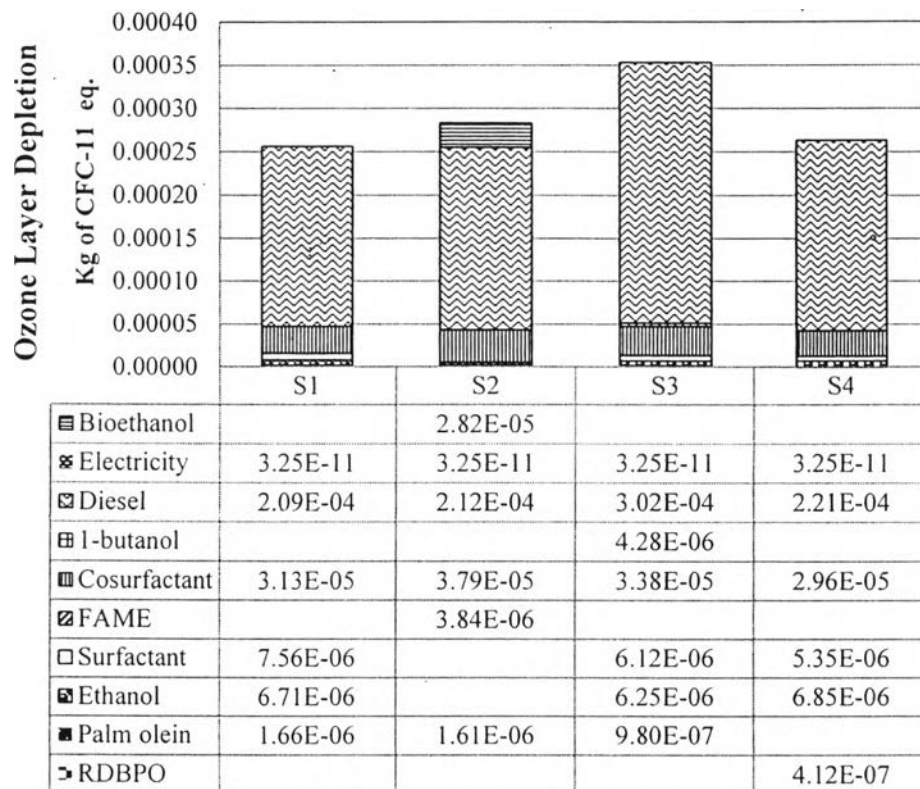
	S1	S2	S3	S4
▤ Bioethanol		2.82E-05		
✳ Electricity	3.25E-11	3.25E-11	3.25E-11	3.25E-11
▨ Diesel	2.09E-04	2.12E-04	3.02E-04	2.21E-04
⊞ 1-butanol			4.28E-06	
▥ Cosurfactant	3.13E-05	3.79E-05	3.38E-05	2.96E-05
▨ FAME		3.84E-06		
☐ Surfactant	7.56E-06		6.12E-06	5.35E-06
▨ Ethanol	6.71E-06		6.25E-06	6.85E-06
▪ Palm olein	1.66E-06	1.61E-06	9.80E-07	
⅂ RDBPO				4.12E-07

Figure 4.6 Ozone layer depletion potential based on 1 ton of ME biofuel.

4.3.1.5 Human Toxicity

Human toxicity refers to chemical, physical or biological substances which 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 effect of toxic substances for an infinite time horizon (during a period of 100 years). Typically, toxicity potential is expressed as the kilogram equivalent of 1,4-dichlorobenzene (DB) (Wibul, 2012) Fig. 4.7 shows the results of human toxicity impact from each ME formulation. Among them, application of bioethanol, especially from cultivation of rye in scenario II contributed the highest human toxicity potential on the environment.
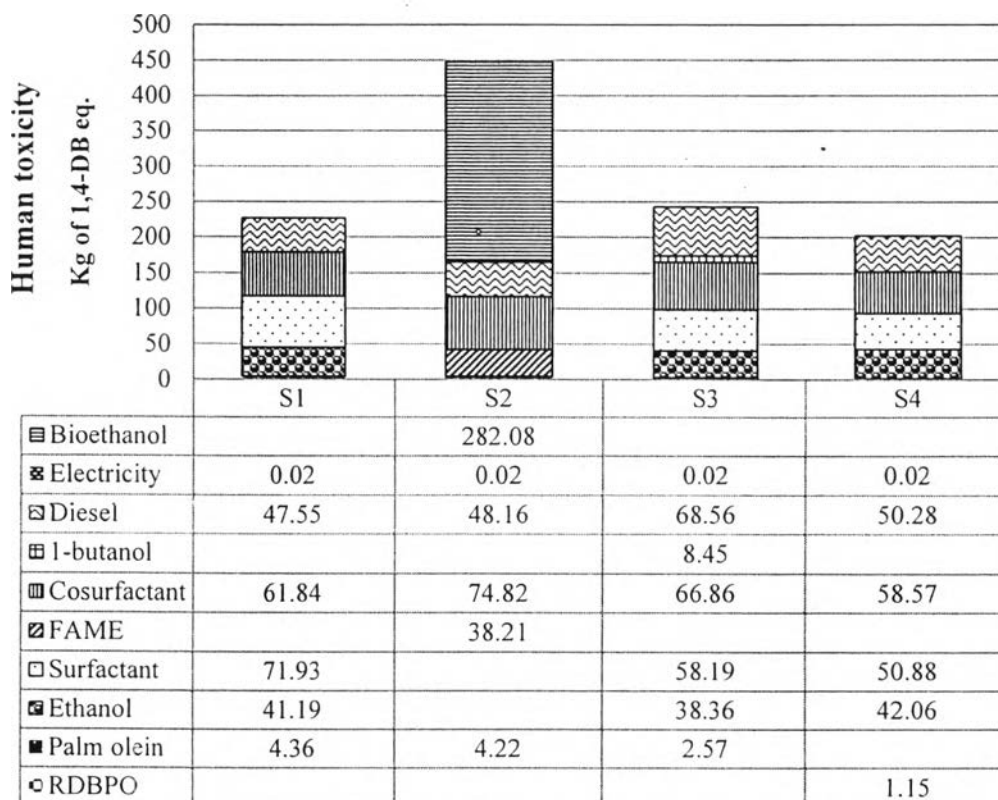
	S1	S2	S3	S4
⊟ Bioethanol		282.08		
⊠ Electricity	0.02	0.02	0.02	0.02
⊠ Diesel	47.55	48.16	68.56	50.28
⊞ 1-butanol			8.45	
⊞ Cosurfactant	61.84	74.82	66.86	58.57
⊠ FAME		38.21		
☐ Surfactant	71.93		58.19	50.88
⊠ Ethanol	41.19		38.36	42.06
■ Palm olein	4.36	4.22	2.57	
○ RDBPO				1.15

Figure 4.7 Human toxicity potential based on 1 ton of ME biofuel.

4.3.1.6 Photochemical Oxidation

Volatile organic compound released during the production of biodiesel typically attributes to photochemical oxidation. The main contributor to photochemical oxidation are volatile organic compounds (VOCs), carbon monoxide (CO) and methane (CH_4). The potential value is expressed in terms of kilogram equivalent of ethylene (C_2H_4) (Wibul, 2012) Fig. 4.8 shows the result of photochemical oxidation impact from each ME formulation. The main contributor was the ethanol production from petrochemical process.
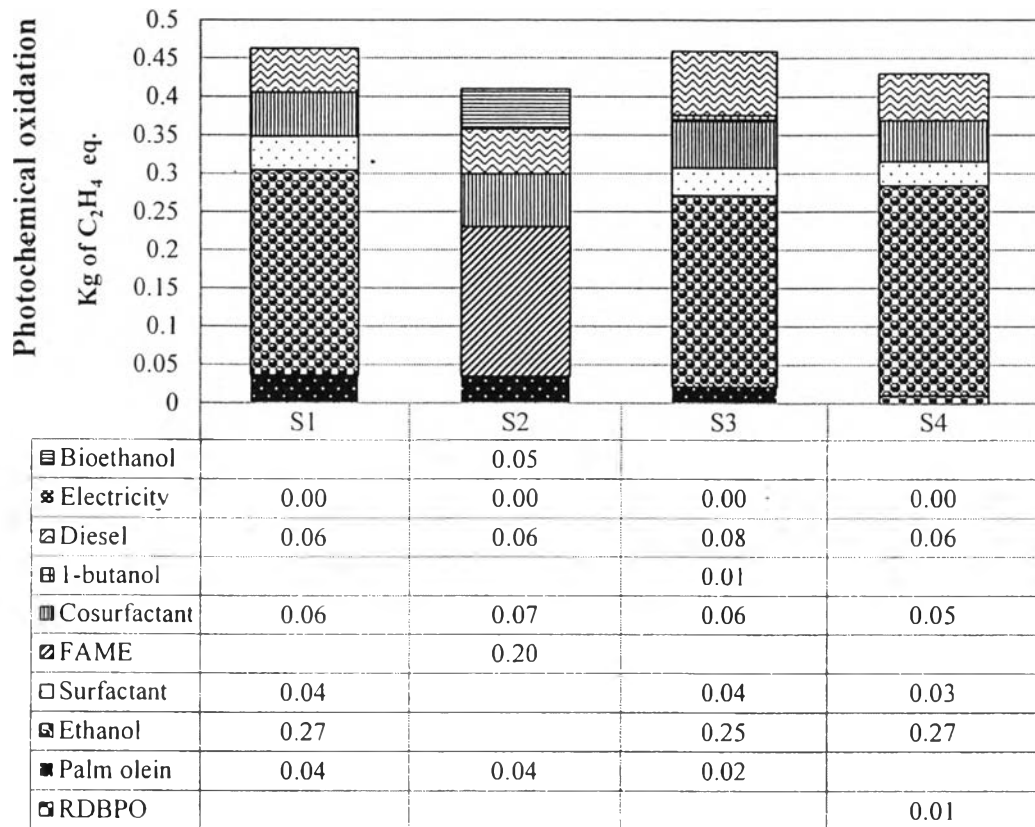
	S1	S2	S3	S4
▤ Bioethanol		0.05		
✿ Electricity	0.00	0.00	0.00	0.00
▨ Diesel	0.06	0.06	0.08	0.06
▦ 1-butanol			0.01	
▥ Cosurfactant	0.06	0.07	0.06	0.05
▧ FAME		0.20		
▢ Surfactant	0.04		0.04	0.03
▩ Ethanol	0.27		0.25	0.27
▪ Palm olein	0.04	0.04	0.02	
◪ RDBPO				0.01

Figure 4.8 Photochemical oxidation potential based on 1 ton of ME biofuel.

4.3.1.7 Eutrophication

Eutrophication is primarily considered as the effect of releasing excessive amount of nutrients, especially nitrate and phosphate. The main contribution to this impact category is expressed in terms of kilogram equivalent of phosphate (PO_4) (Wibul, 2012). Fig. 4.9 shows the results of eutrophication impact from each ME formulation. Among them, scenario II caused the highest eutrophication impact due to the production of bioethanol. Especially, application of nitrogen and phosphorus fertilizers from feedstocks cultivation was the main contributor (Gonzalez-Garcia et al., 2012).
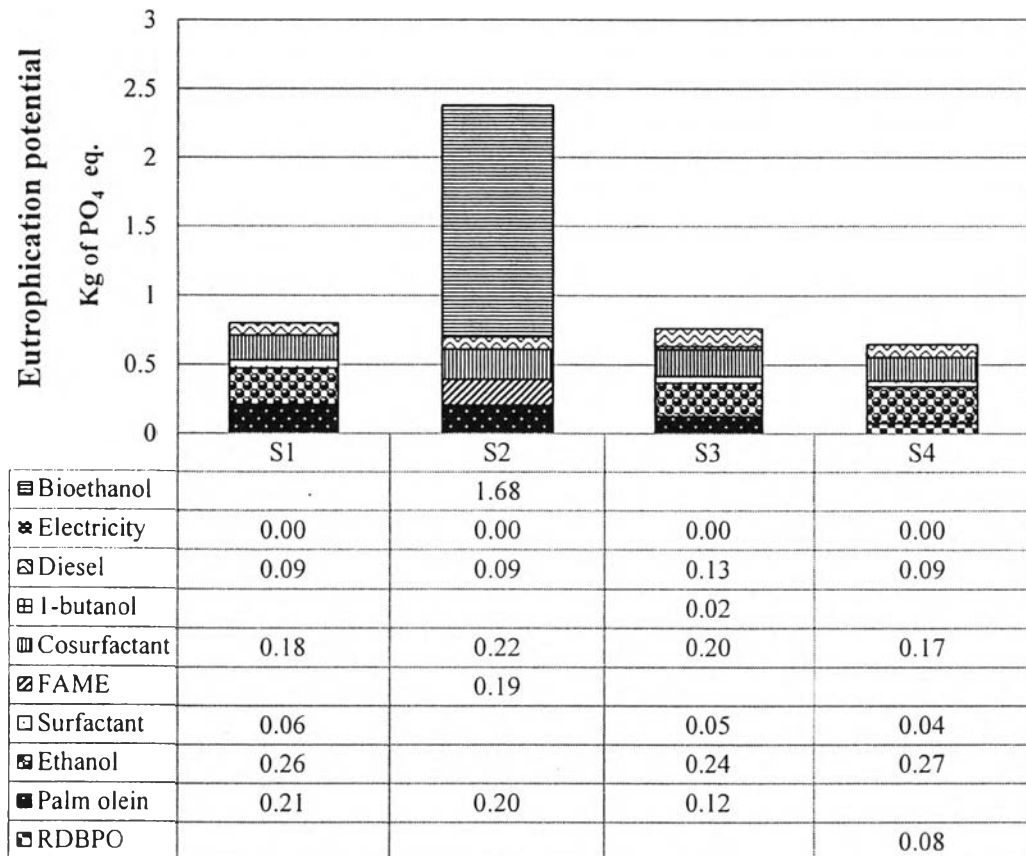
	S1	S2	S3	S4
⊟ Bioethanol	·	1.68		
✖ Electricity	0.00	0.00	0.00	0.00
⊠ Diesel	0.09	0.09	0.13	0.09
⊞ 1-butanol			0.02	
⊞ Cosurfactant	0.18	0.22	0.20	0.17
⊠ FAME		0.19		
☐ Surfactant	0.06		0.05	0.04
⊠ Ethanol	0.26		0.24	0.27
■ Palm olein	0.21	0.20	0.12	
⊠ RDBPO				0.08

Figure 4.9 Eutrophication potential based on 1 ton of ME biofuel.

4.3.1.8 Fresh Water Aquatic Ecotoxicity

Fresh water aquatic ecotoxicity is mainly caused by the emission from agrochemicals such as fertilizers, pesticides and herbicides which normally consist of persistent organic chemicals (chlorinated and polyaromatic hydrocarbon, solvent) and heavy metals. The contribution in this impact category is expressed in terms of kilogram equivalent of 1,4-dichlorobenzene (DB) (Arpornpong , 2014). Fig. 4.10 shows the results of fresh water aquatic ecotoxicity impact from each ME formulation. Among them, Scenario II caused the highest fresh water aquatic ecotoxicity impact also due to the production process of bioethanol.
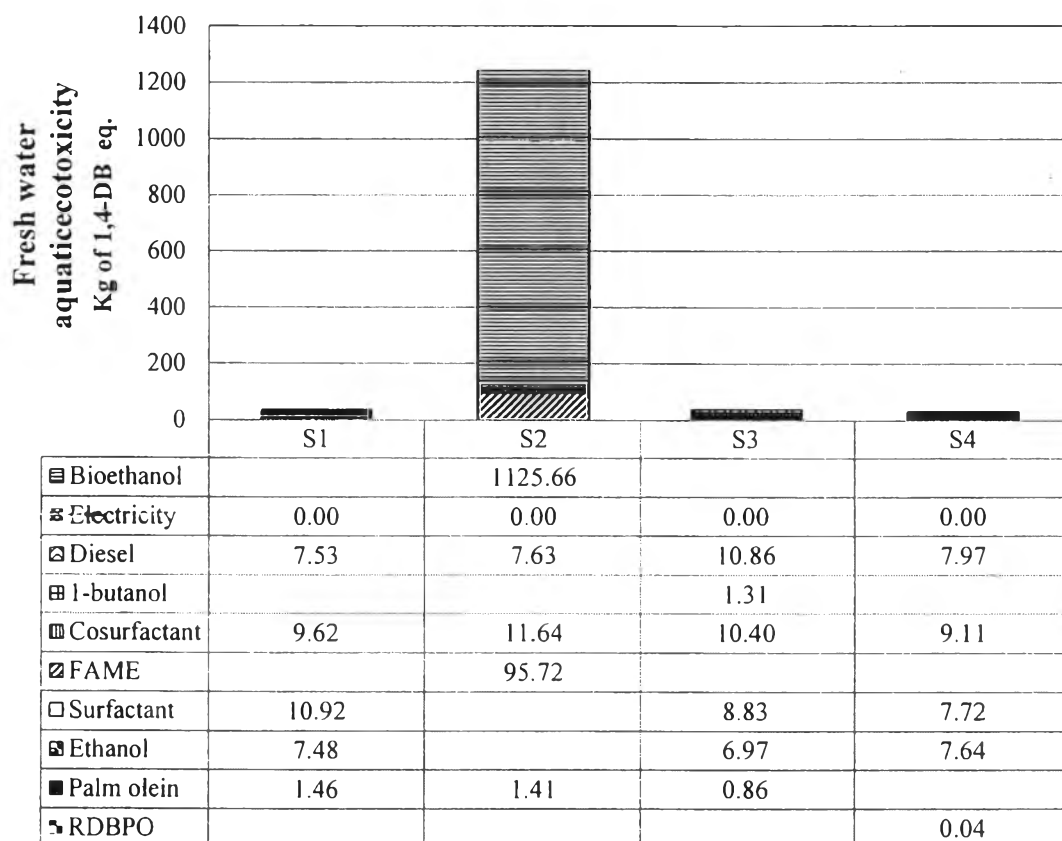
	S1	S2	S3	S4
▤ Bioethanol		1125.66		
▨ Electricity	0.00	0.00	0.00	0.00
▨ Diesel	7.53	7.63	10.86	7.97
▨ 1-butanol			1.31	
▥ Cosurfactant	9.62	11.64	10.40	9.11
▨ FAME		95.72		
☐ Surfactant	10.92		8.83	7.72
▨ Ethanol	7.48		6.97	7.64
■ Palm olein	1.46	1.41	0.86	
▨ RDBPO				0.04

Figure 4.10 Fresh water aquatic ecotoxicity potential based on 1 ton of ME biofuel.

4.3.1.9 Terrestrial Ecotoxicity

Terrestrial ecotoxicity is mainly caused by the emission from agrochemicals such as fertilizers, pesticides and herbicides which normally consist of persistent organic chemicals (chlorinated and polyaromatic hydrocarbon, solvent) and heavy metals. These pollutants not only exit for a long time and also widespread in environment (air, soil, water). The contribution in this impact category is expressed in terms of kilogram equivalent of 1,4-dichlorobenzene (DB) (Arpornpong, 2014). Fig. 4.11 shows the results of terrestrial ecotoxicity impact from each ME formulation. When bioethanol was applied in the formulation, it caused the highest terrestrial ecotoxicity impact on the environment.
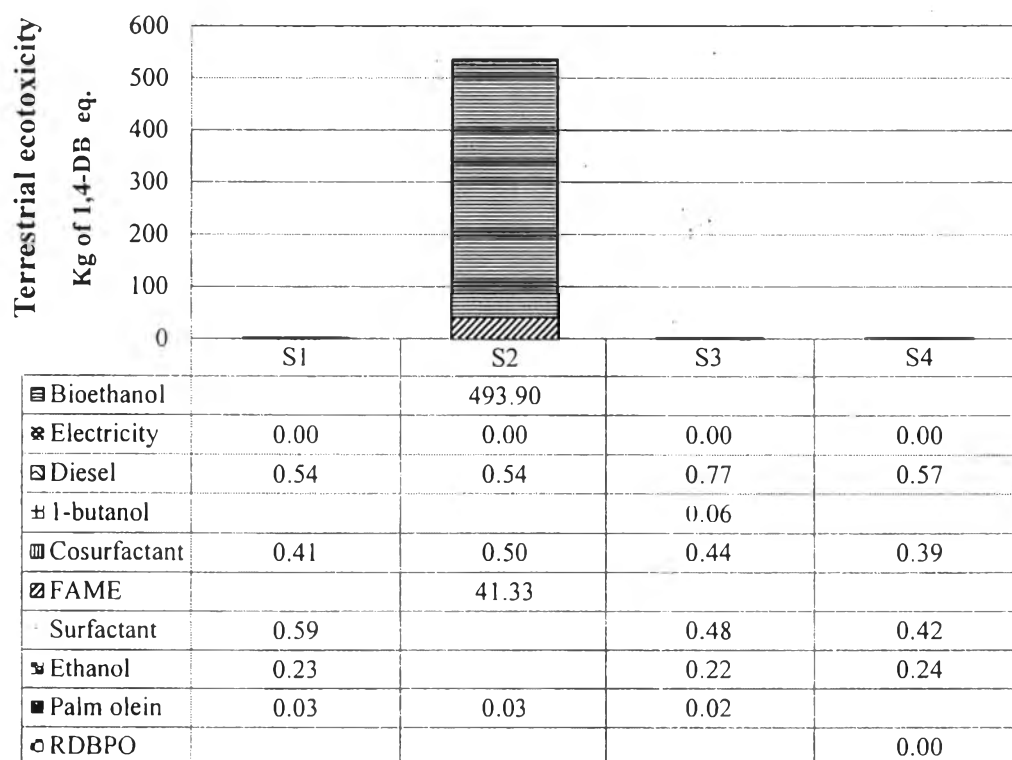
	S1	S2	S3	S4
⊟ Bioethanol		493.90		
✹ Electricity	0.00	0.00	0.00	0.00
⊠ Diesel	0.54	0.54	0.77	0.57
± l-butanol			0.06	
⊞ Cosurfactant	0.41	0.50	0.44	0.39
⊠ FAME		41.33		
Surfactant	0.59		0.48	0.42
❧ Ethanol	0.23		0.22	0.24
■ Palm olein	0.03	0.03	0.02	
⊙ RDBPO				0.00

Figure 4.11 Terrestrial ecotoxicity potential based on 1 ton of ME biofuel.

4.3.1.10 Marine Aquatic Ecotoxicity

Marine aquatic ecotoxicity is mainly caused by the emission of lipophilic organic contaminants, other synthetic compounds and petroleum hydrocarbons are highly resistant to degradation and such compounds or their metabolites may accumulate to high levels in animal tissues and interfere with normal metabolic processes that affect growth, development, and reproduction of marine life. The bioavailability, bioaccumulation, and toxic effects of lipophilic contaminants are related to their pharmacological and toxicological properties (Widdows, 1987) The contribution in this impact category is expressed in terms of kilogram equivalent of 1,4-dichlorobenzene (DB) (Arpornpong , 2014). Fig. 4.12 shows the results of marine aquatic ecotoxicity impact from each ME formulation. Among them, scenario II caused the highest marine aquatic ecotoxicity impact maily from bioethanol production process.
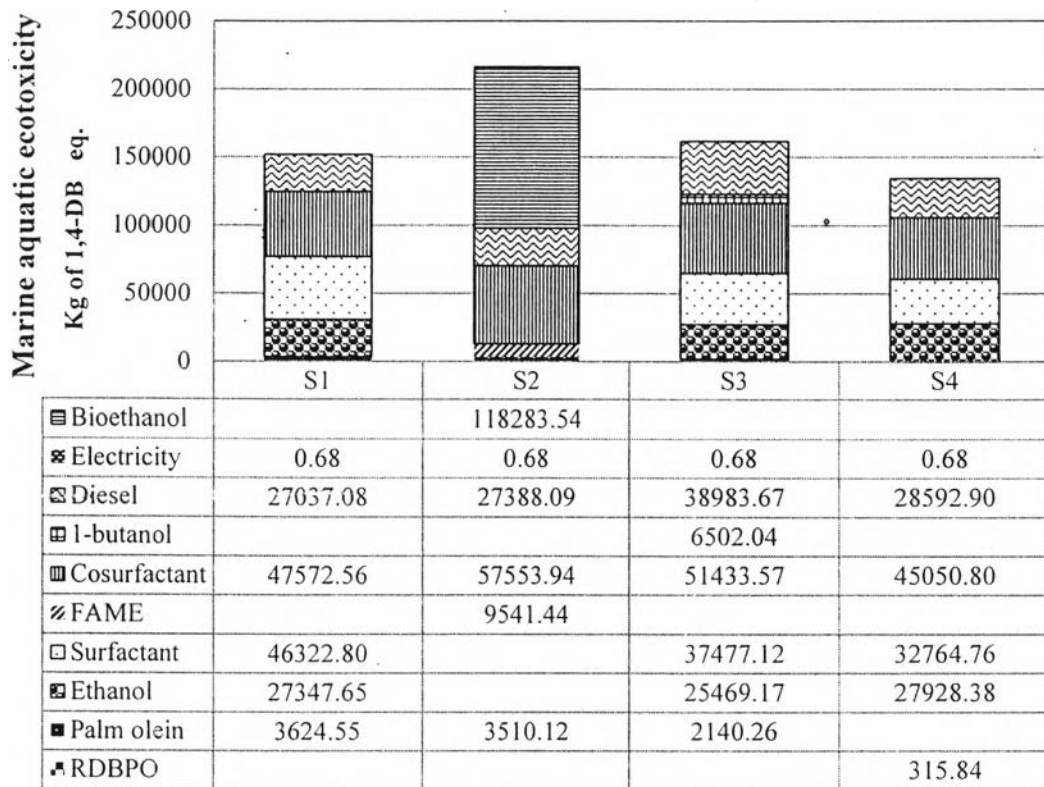
	S1	S2	S3	S4
⊟ Bioethanol		118283.54		
✷ Electricity	0.68	0.68	0.68	0.68
▨ Diesel	27037.08	27388.09	38983.67	28592.90
⊞ 1-butanol			6502.04	
⊞ Cosurfactant	47572.56	57553.94	51433.57	45050.80
⁄⁄ FAME		9541.44		
▢ Surfactant	46322.80		37477.12	32764.76
▨ Ethanol	27347.65		25469.17	27928.38
■ Palm olein	3624.55	3510.12	2140.26	
⋆ RDBPO				315.84

Figure 4.12 Marine aquatic ecotoxicity potential based on 1 ton of ME biofuel.

4.3.1.11 Land Use

The land use (either land occupation or land transformation) is mainly caused by continuous use of land area for a certain human-controlled purposes such as agriculture, raw material production and production processes. The contribution in this impact category is expressed in terms of PDF m^2 yr. (Arpornpong *et al.*, 2013) Fig. 4.13 shows the results of land use impact from each ME formulation. Among them, scenario II caused the highest land use change impact because of the production of bioethanol. Especially, the bio-based feedstock cultivation was the main contributor of land use impact because a large area is required for cultivation of crop.

	S1	S2	S3	S4
▤ Bioethanol		3738.06		
✹ Electricity	0.00	0.00	0.00	0.00
◪ Diesel	3.28	3.32	4.73	3.47
⊞ 1-butanol			0.31	
▥ Cosurfactant	2.29	2.77	2.47	2.17
▨ FAME		170.43		
☐ Surfactant	1.23		1.00	0.87
▨ Ethanol	0.93		0.86	0.95
■ Palm olein	0.42	0.41	0.25	
▣ RDBPO				0.07
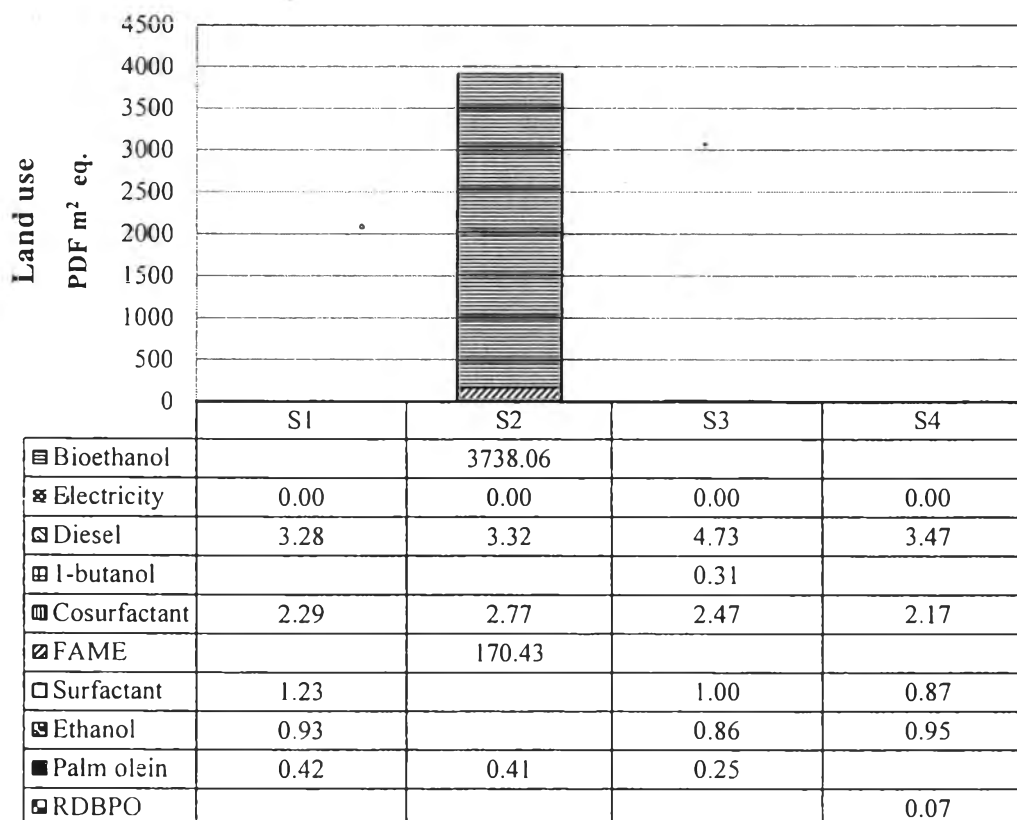
Figure 4.13 Land use potential based on 1 ton of ME biofuel.

4.3.2 Comparison of Environmental Impacts

The emissions of each impact category from four scenarios were compared based on the normalized results of each impact obtained from the SigmaPro software. According to the Fig. 4.14, main contributor to most of the impacts was microemulsion stage more than 60 percent contribution.

According to the results from SimaPro's impact assessment methods, cosurfactant causes significant toxic effects on environment and contributes to some impact categories such as photochemical oxidation, marine aquatic ecotoxicity, fresh water aquatic ecotoxicity, human toxicity and eutrophication. Among other materials used in ME formulation, diesel usage imparts highest contribution for land use change and abiotic depletion impact categories.
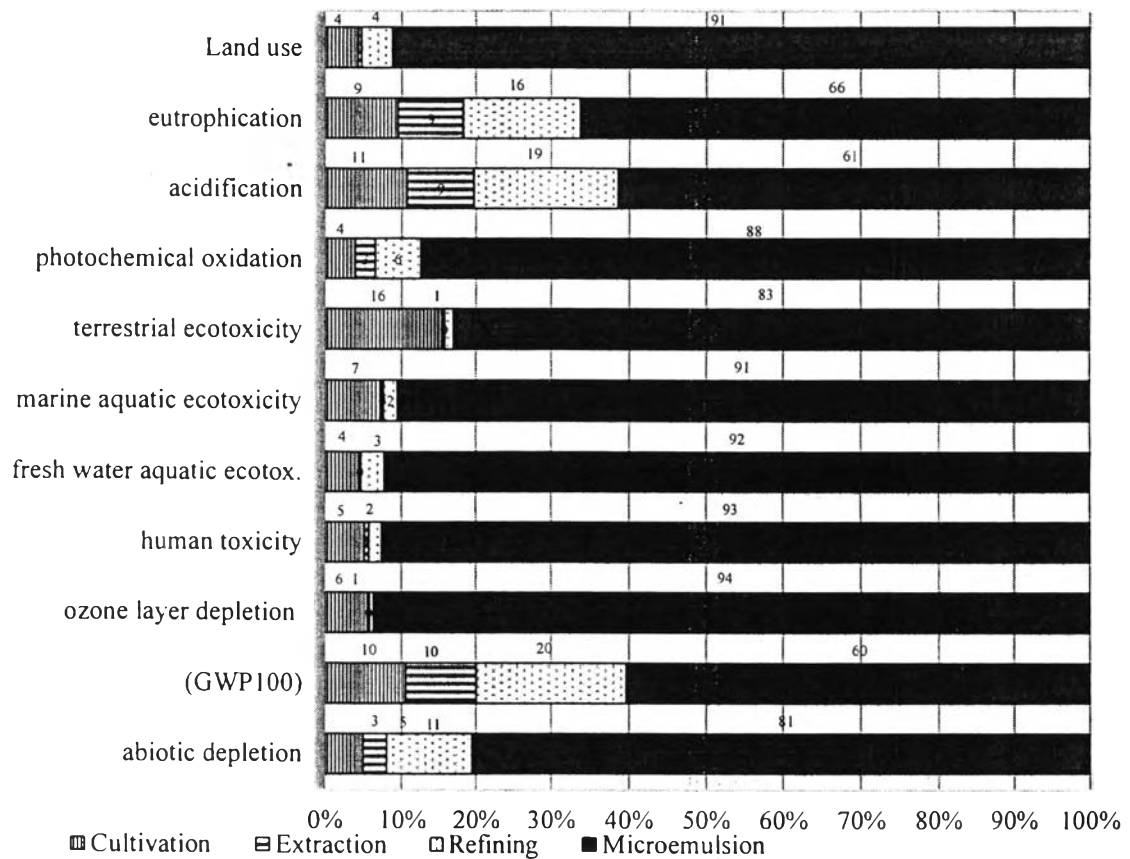
Figure 4.14 Comparison of environmental impacts related to cultivation (base case), extraction (base case), refining (base case) and microemulsion (scenario IV).

According to Fig. 4.15, Scenario IV (RBDPO case) contributed minimum GHG emission among other scenarios. In addition, Scenario II imparted significant effect to most impact categories such as eutrophication, acidification, fresh water aquatic ecotoxicity and terrestrial ecotoxicity.

In Scenario II (biobased case), production of bioethanol is the major cause to some impact categories, such as eutrophication, terrestrial ecotoxicity and fresh water aquatic ecotoxicity. According to the results of the formulation of Scenario I (base case), palm olein production contributes a significant GHG emission potential to the environment.
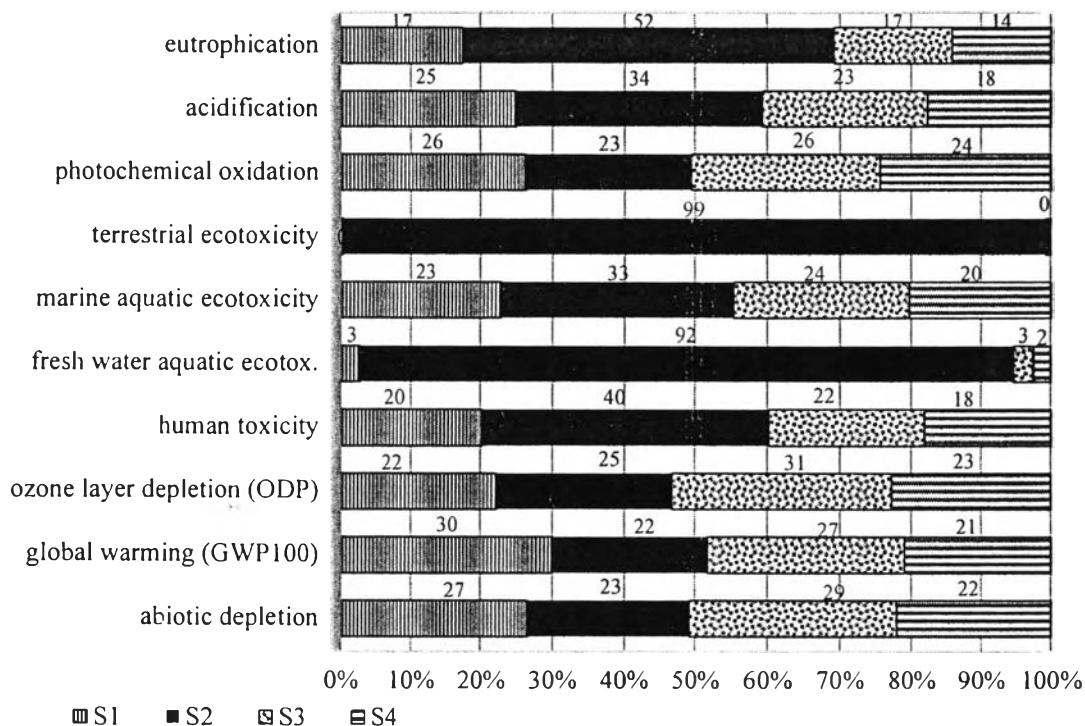
Figure 4.15 Comparison of environmental impacts related to different ME formulation.

4.4 Sensitivity Analysis

4.4.1 Sensitivity Analysis for GHG Emission

Sensitivity analysis was carried out in the case of biogas recovery from palm oil mill effluent in order to observe the influence on GHG gas emission from each Scenario. In addition, energy recovered from biogas recovery of each Scenario were also taken into account. Methane yield is 0.251kg/kg of COD (Arpornpong *et al.,* 2014). Density of methane is 0.656 kg/m3 and LHV of methane is 23 MJ/m3 (Arpornpong *et al.,* 2014). Energy recovered was converted to electricity in the unit of kWh. The reduction of GHG emission from each Scenario result from selling of electricity generated from biogas to Provincial ElectricityAuthority (PEA), Thailand through the grid. The results of the sensitivity analysis from each Scenario are illustrated in Fig. 4.16. According to sensitivity analysis, biogas capture from POME reduced 48 % from the GHG emission of Scenario I, 44% from Scenario II, 27% from Scenario III and 21 % from Scenario

IV. The emission factor for methane (23 kg CO_2 eq./ kg of methane) was obtained from Ecoinvent version 2.0 database and the carbon footprint calculation method used in this calculation is shown in following equation (PAS, 2050). Electricity in the unit of (kWh) generated from methane were 283, 272, 166 and 127 for Scenario I, II, III and IV respectively.

Carbon footprint of given activity =Activity data(mass, volume, kWh, km)

× Emission factor (CO_2 eq. per unit)
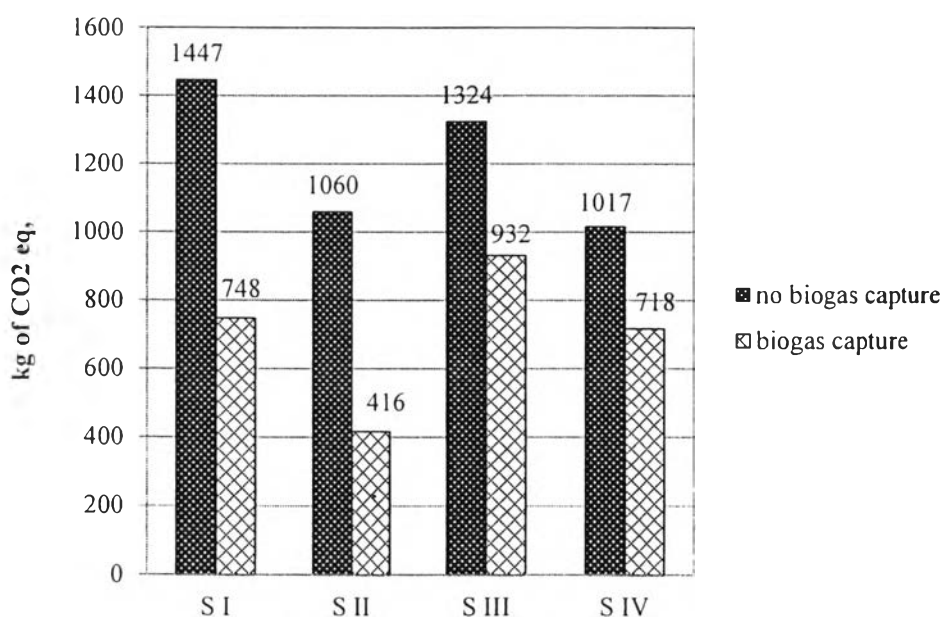
Figure 4.16 Comparison of GHG emissions with and without biogas capture.

4.4.2 Sensitivity Analysis for Environmental Impacts

Sensitivity analysis was conducted in the case of bioethanol production. Although bioethanol (95% in H_2O, from rye) blended in the Scenario II (Biobase Case) microemulsion formulation imparted satisfactory GHG emission, it contributed significant unsatisfactory effects to human and water system and caused high negative potential to some impact categories such as eutrophication, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and land use change. Major contribution came especially from the cultivation of rye which required the fertilizer loading (300-120-180 kg/ ha) for N-P-

K fertilizers (Synder and Thompson, 1996). Fig. 4.17 and 4.18 represented that bioethanol (95% in H_2O, from grass, vetiver) could reduce environmental impacts such as terrestrial ecotoxicity, human toxicity, fresh water aquatic ecotoxicity, eutrophication, marine aquatic ecotoxicity and land use change effectively because vetiver grass can be grown on very infertile soil and minimum fertilizer loading is required to establish vetiver grass (Truong, 2007).
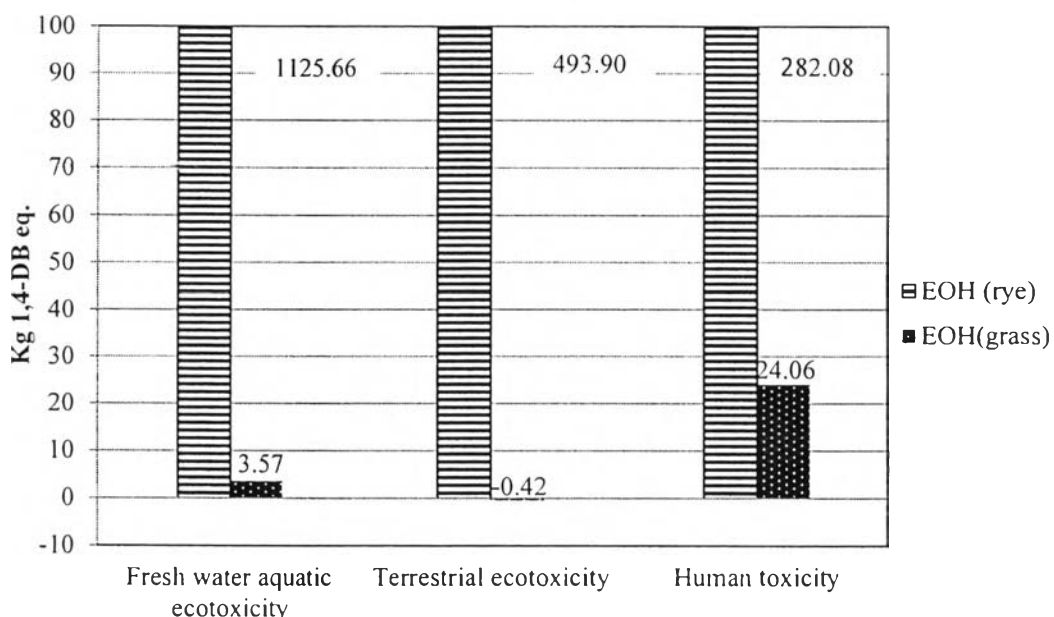

Figure 4.17 Comparison of different bioethanol used in Scenario II (Biobase Case) for fresh water aquatic ecotoxicity, terrestrial ecotoxicity and human toxicity impacts
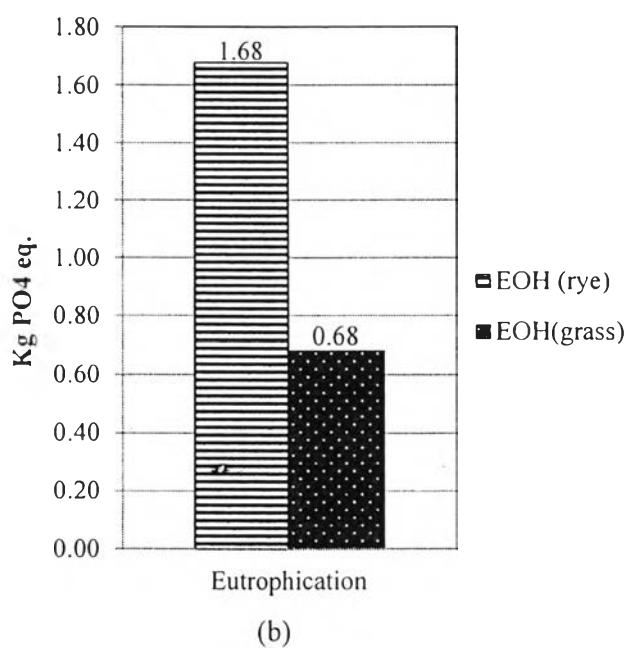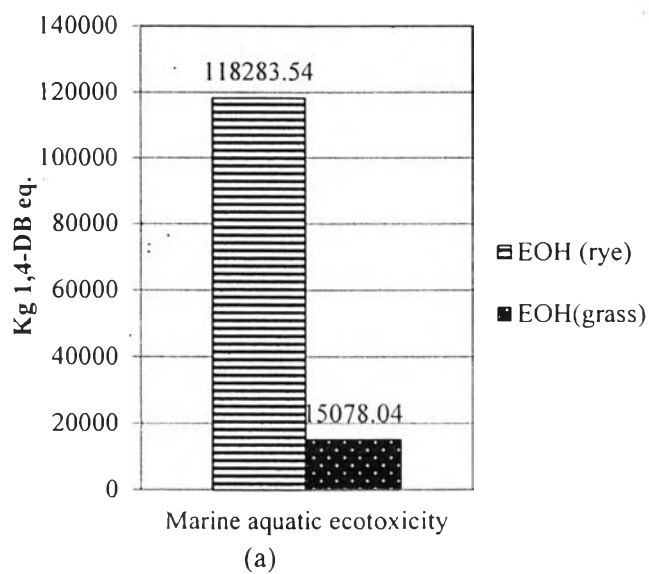
Figure 4.18 Comparison of different bioethanol used in Scenario II (Biobase Case)
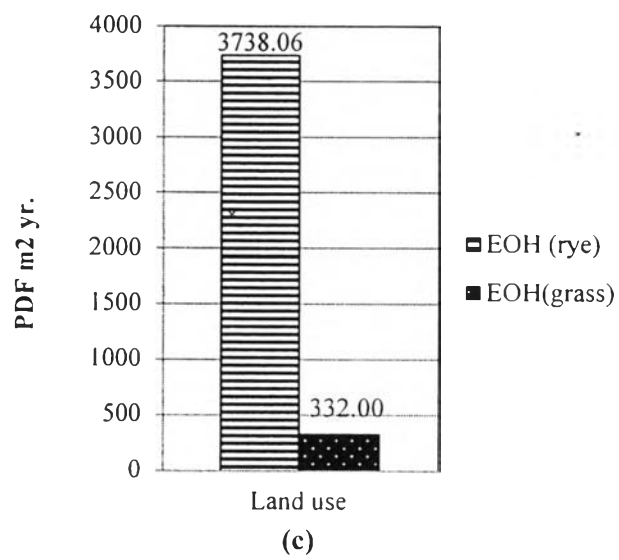for (a) Marine aquatic ecotoxicity and (b) Eutrophication (Continue).

Figure 4.18 Comparison of different bioethanol used in Scenario II (Biobase Case) for Land use change (c) impact.