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Life Cycle Assessment Comparison between Methanol and Ethanol Feedstock for the Biodiesel from Soybean Oil

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Abstract**—**As the limited availability of petroleum-based fuel has been a major concern, biodiesel is one of the most attractive alternative fuels because it is renewable and it also has advantages over the conventional petroleum-base diesel. At Present, productions of biodiesel generally perform by transesterification of vegetable oils with low molecular weight alcohol, mainly methanol, using chemical catalysts. Methanol is petrochemical product that makes biodiesel producing from methanol to be not pure renewable energy source. Therefore, ethanol as a product produced by fermentation processes. It appears as a potential feed stock that makes biodiesel to be pure renewable alternative fuel. The research is conducted based on two biodiesel production processes by reacting soybean oils with methanol and ethanol. Life cycle assessment was carried out in order to evaluate the environmental impacts and to identify the process alternative. Nine mid-point impact categories are investigated. The results indicate that better performance on abiotic depletion potential (ADP) and acidification potential (AP) are observed in biodiesel production from methanol when compared with biodiesel production from ethanol due to less energy consumption during the production processes. Except for ADP and AP, using methanol as feed stock does not show any advantages over biodiesel from ethanol. The single score method is also included in this study in order to identify the best option between two processes of biodiesel production. The global normalization and weighting factor based on ecotaxes are used and it shows that producing biodiesel form ethanol has less environmental load compare to biodiesel from methanol.

Keywords**—**Biodiesel, Ethanol**,** Life Cycle Assessment, Methanol**,** Soybean Oil.

I. INTRODUCTION

PRESENTLY, the limited availability of petroleum-based fuel has been a major concern [1]. As the global energy consumption is rapidly increasing, our main fossil fuel resources are constantly declining and it is predicted that they will soon fail to meet global demand [2]. The shortage of crude oil is inevitable; therefore, the production of alternative fuels has been receiving significant interest from researchers around the world. Biodiesel is one of the most attractive alternative fuels because it has advantages over the conventional petroleum-base diesel. These advantages include low sulfur content, biodegradability, and net zero carbon dioxide emission. Moreover, biodiesel shares many properties with petro diesel [3], including specific gravity, flash point, cloud point, pour point, viscosity, and octane number. As a result, biodiesel can directly replace conventional diesel.

Biodiesel is produced from vegetable oils or animal fats which contain triglycerides (TG) and free fatty acids (FFA).

$$\text{TG} + 3\text{Alcohol} \longleftrightarrow 3\text{Biodiesel} + \text{Glycerol} \qquad (1)$$

Reaction (1) shows transesterification of triglycerides and low molecular weight alcohol to produce biodiesel and glycerol as by-product. Generally, undergoes in homogeneous base catalyst environment [3], [4]. Stoichiometrically, a higher molar ratio of alcohol to oil is required to obtain greater conversion [5].

There are various kinds of oils that are suitable to become feed stock for biodiesel production. Examples are soybean oil [6], [7], palm oil [8], waste cooking-oils [3], and Jatropha oil [9]. Among those potential feed stocks, soybean oil has been chosen to be the target of this study. The attractive advantages of using soybean oil are;

- Cultivation conditions are suitable for Thailand [10], [11].
- Short life cycle [10], [11]
- Low free fatty acid content [12]

At Present, productions of biodiesel generally perform by transesterification of vegetable oils with low molecular weight alcohol, mainly methanol, using chemical catalysts [13]. Methanol is petrochemical product that makes biodiesel producing from methanol to be not pure renewable energy source [14]. Therefore, ethanol as a product produced by fermentation processes using biomass from varies sources appears as a potential feed stock that makes biodiesel to be pure renewable alternative fuel [15], [16]. However, environmental analysis has to be analyzed to design which one should be the potential feed stock.

Life cycle assessment or LCA is a tool to identify the environment impacts of the product. It means that product is followed from its “cradle” where raw materials are extracted from natural resources through production and use to its “grave”, the disposal. The impact is analyzed by separating into categories in a quantitative way. Life cycle assessment has been applied in product development, product improvement, and product comparison [17].

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The present work deals with transesterification of soybean oil to biodiesel using different alcohol feed stock (methanol and ethanol) which result in different production process. These two processes were investigated in order to evaluate and compare the environmental impact; life cycle assessment (LCA) is the method using to evaluate the impact. The inventory data needed to investigate including agriculture process, transportation of feedstock, production of biodiesel, transportation of biodiesel, and final vehicle operation. Process design alternatives are investigated using the Aspen plus simulation program to estimate the inventory data for these two biodiesel production processes, with same plant capacity and product purity. The kinetic models can be obtained based on the experimental results of other researchers.

II. METHODOLOGY

A. Objective

The main objective of the study is to evaluate and compare the environmental impact, to identify the most important environmental load, and to identify the best process alternative on two biodiesel production processes, which are produced by reacting soybean oils with methanol and ethanol, respectively.

B. Functional Unit

Functional unit is chosen to provide a basis for calculating input and output. Selecting the wrong functional unit will lead to an error in life-cycle inventory. In comparison between energy production processes, functional unit is usually set to be the energy content of final product. As energy content can be assumed to be equal for biodiesel derived from methanol and ethanol [18], the functional unit in this study is set to be 1000kg of final product.

C. System Boundary and Inventory Data

Figs. 1 and 2 show the life cycle system of biodiesel production processes with methanol and ethanol, respectively. The process includes agriculture, oil extraction, alcohol production, production of biodiesel, and steam and electricity production. All of the inputs, product outputs, and emissions in the life cycle of different alcohol feedstock based biodiesel are summarized in Table I. Inventory data are mainly derived from recent studies on relevant processes and the missing data are estimated by using ASPEN Plus simulation program.

1. Soybean Cultivation

The following assumptions were made: natural process was used to remove unwanted plants, farming process was done without using agricultural machineries, material inputs and outputs were taken from Thailand Ministry of Agriculture and Cooperatives and local farmer in Thailand, and the information about average CO_2 uptake was obtained from Luis P. et al. (2008) [19].

2. Soybean Oil Extraction

Three stages of soybean oil processing were studied in detail including preprocessing, solvent extraction and separation, and post processing. Material and energy inputs/outputs were obtained from Yong Li et al. (2006) [20].

3. Methanol Production

In this study, methanol was derived from natural gas. Three main processes were analyzed including synthesis gas production, methanol production, and purification. Material and energy inputs/outputs were taken from master thesis of Theophilus Arthur [14].

4. Ethanol Production

Ethanol was produced by fermentation of molasses using a strain of *Saccharomyces cerevisiae* (LPB-SC). The LCA considerations and assumptions are listed as follow: molasses production was ignored because it is considered as a by-product and has low economical value, mass balance base on industrial data were obtain from the work of Paula F. et al. (2008) [16], and energy inputs and outputs were estimated base on hand calculation and simulation program (ASPEN Plus).

5. Biodiesel Production

FAME and FAEE were synthesized via tranesterification in batch reactor. In the FAME production, 90% conversion of methyl ester was obtained at 70°C, 6:1 molar ratio of alcohol to triglycerol, and 0.2 wt% of sodium hydroxide based on soybean oil [6]. On the other hand, ethyl ester yield of 97.2% was obtained at 70°C, 12:1 molar ratio of alcohol to triglycerol, and 0.2 wt% of sodium hydroxide based on soybean oil [7]. Material and energy balance associated with biodiesel production processes were estimated based on ASPEN Plus program with the same plant capacity and product purity.

6. Steam and Electricity Production

In steam and electricity production, natural gas was assumed to be as the only source to generate heat and electricity. Energy content of natural gas was taken from GaBi software. The emission and efficiency of electricity generation of natural gas was obtained from U.S. Energy Information Administration (EIA) [21]-[23]. The efficiency of steam production was obtained from The Office of Energy Efficiency and Renewable Energy (EERE) [24].

D. Life Cycle Allocation

Allocation methods are needed when two or more products share the same production process. There are several processes in both biodiesel production from methanol and ethanol including oil extraction, ethanol production, and biodiesel production that have co-products generated. In this study, the economic allocation was applied. This is advised as a baseline method for most allocation situations. The pricing data were obtained from varies sources such as CME globex for soybean oil and de-oil soybean [25], ICSI pricing for biodiesel [26], and Thomson Reuter for glycerin [27]. It was found that co-product from ethanol production (vinasses) was not had the economical value and was used as an intermediate in other processes, which did not include in this work. Therefore, vinasses were not considered to have an environmental effect with regards to the scope of this study.

E. Life Cycle Impact Assessment

The potential environmental impact can include: Abiotic depletion potential (ADP), Global warming potential (GWP), Photochemical oxidation potential (POCP), Acidification potential (AP), Eutrophication potential (EP), Human toxicity potential (HTP), Fresh water aquatic ecotoxicity potential (FAETP), Marine aquatic ecotoxicity potential (MAETP), and Terrestric ecotoxicity potential (TETP).

TABLE I
INPUTS, OUTPUTS, AND EMISSIONS IN THE LIFE CYCLE SYSTEM

Stages	**Input/Output**	**Methanol based**		**Ethanol based**
Cultivation	***Input***			
	Carbon Dioxide (kg)	7004.774		6686.653
	Fertilizer(kg)			
	Ammonium Sulphate	145.750		139.131
	Ammonium Phosphatemonobasic	29.862		28.506
	Ammonium Phosphatebibasic	86.808		82.865
	Carbonyldiamide (urea)	26.042		24.860
	Potassium Chloride	124.369		118.721
	Insecticide (g)			
	Triazophos	1.389		1.326
	Imidacloprid	170.143		23.202
	Carbosulfan	1.667		1.591
	Carbofuran	2083.385		1988.768
	Fipronil	0.139		0.133
	Output			
	Soybean (kg)	5112.974		4880.769
	Fertilizer (g)			
	Ammonium Sulphate	6796.868		6488.189
	Ammonium Phosphatemonobasic	3.247		3.100
	Ammonium Phosphatebibasic	50.467		48.175
	Carbonyldiamide (urea)	156.689		149.573
	Potassium Chloride	1809.623		1727.439
	Insecticide (g)			
	Triazophos	1.034		0.987
	Imidacloprid	8.898		1.213
	Carbosulfan	1.619		1.546
	Carbofuran	753.144		718.940
	Fipronil	0.008		0.007
Oil extraction	***Input***			
	Soybean (kg)	5112.974		4880.769
	Solvent (kg)			
	n-hexane	31.700		30.261
	2-methylpentane	12.271		11.714
	Methycyclolpentane	6.647		6.345
	2,2-diomethylbutane	0.511		0.488
	Energy (MJ)			
	Fuel	3105.621		2964.579
	Electricity	293.485		280.156
	Output			
	Soybean oil (kg)	997.030		951.750
	De-oil soybean (kg)	3754.759		3584.237
	Solvent (kg)			
	n-hexane	31.700		30.261
	2-methylpentane	12.271		11.714
	Methycyclolpentane	6.647		6.345
	2,2-diomethylbutane	0.511		0.488
Alcohol Production	***Input***		***Input***	
	Water (kg)	19.077	Molasses (kg)	1566.936
	Methane (kg)	3.928	Water (kg)	4309.074
	Ethane (kg)	0.123	Ethylene Glycol (kg)	0.16

	Propane (kg)	0.021	**Energy(MJ)**	
	Butane (kg)	0.016	Fuel	5375.052
	Nitrogen (kg)	0.025	Electricity	4196.337
	Oxygen (kg)	2.267	***Output***	
	Energy(MJ)		Ethanol (kg)	151.027
	Fuel	1925.466	Venasse (kg)	4382.165
	Electricity	428.697	Water	*1342.818*
	Output		Ethanol	0.026
	Methanol(kg)	109.651	Ethylene Glycol	0.16
	Waste water (kg)			
	Water	2.493		
	Methanol	0.002		
	Carbon Dioxide	0.001		
	Off Gas (kg)			
	Methanol	0.425		
	Carbon Monoxide	13.975		
	Carbon Dioxide	10.953		
	Steam	21.477		
	Methane	1.789		
	Hydrogen	1.385		
	Nitrogen	0.028		
Biodiesel Production	***Input***			
	Soybean oil (kg)	997.03		951.75
	Alcohol (kg)	109.651		151.027
	Water (kg)	1719		1719
	Sodium Hydroxide (kg)	2.216		2.936
	Hydrochloric acid (kg)	2.02		2.677
	Energy (MJ)			
	Fuel	6291.31		8821.179
	Electricity	5482.947		8196.241
	Output			
	Biodiesel (kg)	1000		1000
	Glycerol (kg)	103		103
	Waste water (kg)			
	H2O	1672.736		1704.948
	MEOH	1.328		0.427
	Glycerol	1.415		2.201
	NaCl	3.15		4.254
Steam and Electricity Production	***Input***			
	Natural gas	735.436		1326.829
	Output			
	Carbon Monoxide	0.524		0.946
	Carbon Dioxide	1533.84		2767.266
	Sulfur Dioxide	0.013		0.024
	NO_x	1.206		2.176

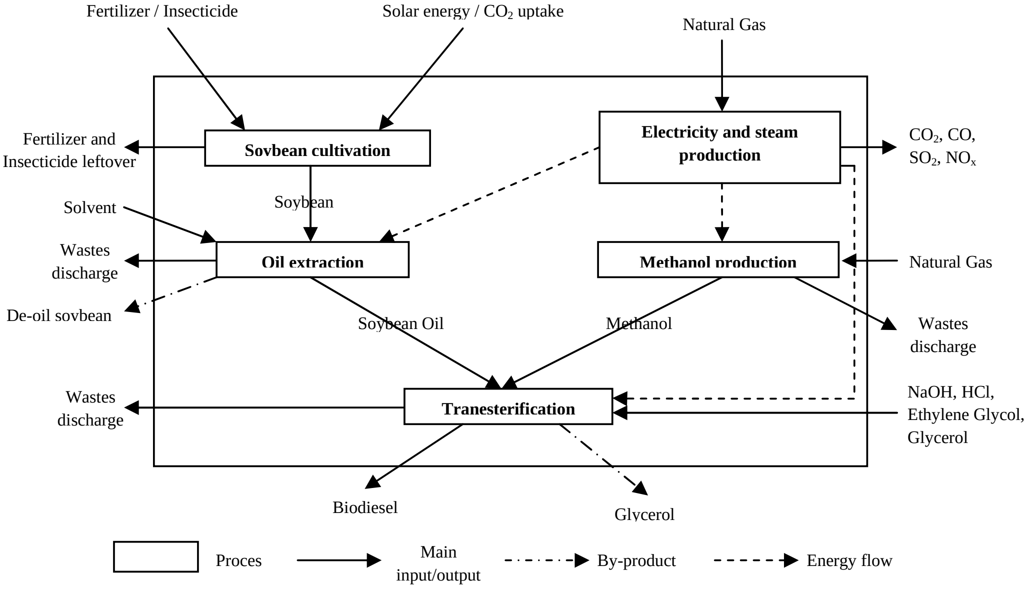

Fig. 1 Life cycle system of methanol based biodiesel production

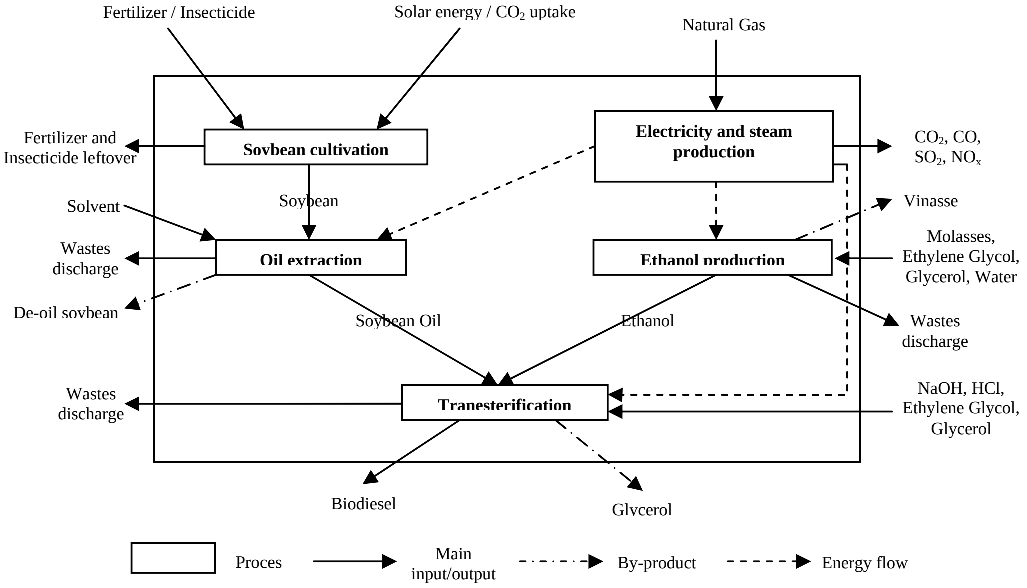

Fig. 2 Life cycle system of ethanol based biodiesel production

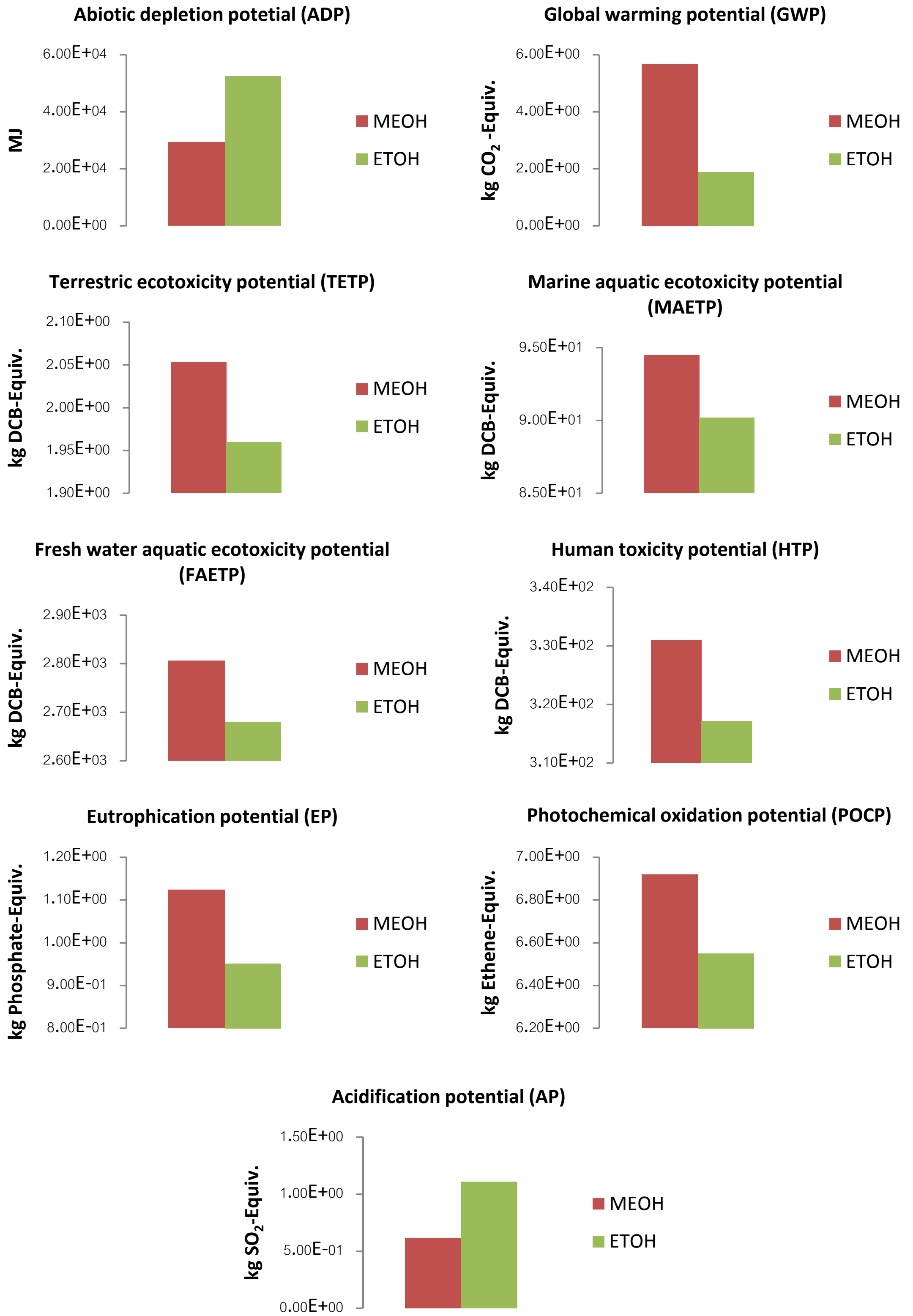

Fig. 3 Comparative LCA Results per Impact Categories

F. Interpretation

The comparative environmental evaluation is performed to understand the environmental load contributed to specific processes per impact category, and to determine the reasons of the change of environmental impacts of biodiesel production process using different alcohol feedstocks (methanol and ethanol).

III. RESULT AND DISCUSSION

Five processes of biodiesel production were considered in this study including soybean cultivation, soybean oil extraction, alcohol production, biodiesel production, and steam and electricity production. These five processes were described in details in system boundary and inventory data part. In this work, biodiesel production is separated into two cases: Case 1 for the methanol feed stock and Case 2 for the ethanol feed stock. The functional unit was set to 1000 kg of biodiesel and natural gas was assumed to be the only heating source to produce heat and electricity. Fig. 3 shows the comparative LCA results per impact categories of methanol and ethanol bested biodiesel.

When compared with methanol based biodiesel, the life cycle ADP and AP of biodiesel from ethanol are higher by 44.1% and 44.5%, respectively. Separation process plays an important role to this significant difference. About 40% higher amount of heat was used in biodiesel production from ethanol. Unlike methanol, ethanol forms azeotrope with water, which causes separation problem. In this study, ethanol and water were separated by using extractive distillation having ethylene glycol mixed with glycerol as an entertainer that was the primary reason of the significant increase in energy consumption. The more energy used, the more fuel (abiotic resource) was consumed. More air pollutant was also emitted but only affect to AP. It should also result in the increasing of Global Warming Potential (GWP) but it was not. GWP is decreased by 66% compared to biodiesel from methanol. The reason of this significant decrease is that the large amount of CO_2 uptake in cultivation of soybean, which is cover all emitted CO_2 in biodiesel production. Moreover, in methanol production process, emission of methane has strongly effect in impact of GWP.

As can be seen in Fig. 3, except for ADP and AP, using methanol as feed stock did not show any advantages over biodiesel from ethanol. Photochemical oxidation potential (POCP) was increased by 5.3%. It was mainly caused by the emission of solvents in soybean oil extraction process. Around 51.1 kg of solvents were discharged in methanol based biodiesel while 48.8 kg were leaked in ethanol based biodiesel. The solvent composes of four substances, which are hexane, 3-methylpentane, methyl cyclopentane, and 2,3-dimethylbutane.

Eutrophication potential, human toxicity potential, fresh water aquatic ecotoxicity potential, marine aquatic ecotoxicity potential and terrestric ecotoxicity potential were all about 0.05 times higher. It was found that the higher in these four categories was mainly come from the emission during soybean cultivation. The emissions of ammonium and phosphate from fertilizer to environment had significant effect to eutrophication potential. For the other three categories, the used of insecticides was the main contributor.

Even though both of biodiesel production processes used the same chemicals but unequal amount of chemicals were leaked to the environment. Biodiesel from methanol required larger amount of feedstock to produce the same amount of biodiesel. The increase of feed stock leads to larger amount of chemicals discharged to the environment. Therefore, the environmental load of biodiesel from methanol was higher in most of impact categories.

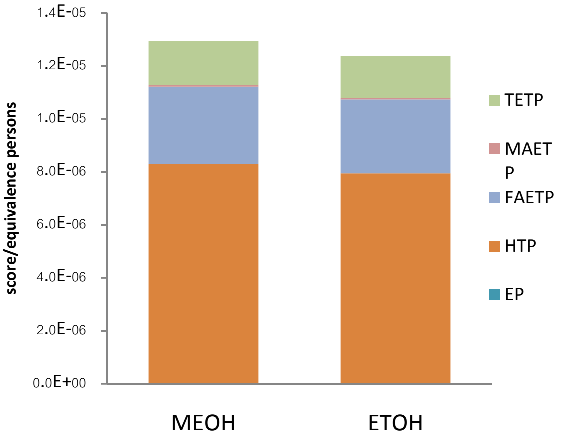

Fig. 4 Comparison of LCA Single Score Result

Fig. 4 shows comparison of the impact assessment using single score method. This method was introduced to identify the best option among biodiesel from methanol feedstock and biodiesel from ethanol feedstock. All of nine mid-point impact categories were combined into one single score by using global normalization and weighting factors. In this study, the information about normalization and weighting factors were obtained from Sleeswijk et al. (2008) [28] and Finnveden et al. (2006) [29], respectively. The result is in the unit of score/equivalence persons (the number of equivalent persons affected during one year per unit of emission).

The result shows that biodiesel production from ethanol feedstock has less environmental load when compared with biodiesel production from methanol. From Fig. 2, there are three main impact categories that contribute more than 99% of the total score. These are human toxicity, fresh water aquatic ecotoxicity, and terrestric ecotoxicity, which are mainly caused by the emission of agrochemical from soybean cultivation. The improvement of agricultural process will result in signification reduction in environmental impact.

IV. CONCLUSION

This research was conducted based on two biodiesel production processes with different alcohol feedstocks: methanol and ethanol. The research aimed to evaluate and compare the environmental performances of the two processes of biodiesel production. The results show that producing biodiesel from ethanol had a significantly higher impact on abiotic depletion potential (ADP) and acidification potential (AP). The main cause was the steam and electricity production. More steam and electricity are required in biodiesel from ethanol that lead to higher consumption of natural gas and emission from burning natural gas in producing steam and electricity. The emission from burning natural gas should also contribute to higher impact in global warming potential (GWP). However, lower in GWP was observed in biodiesel from ethanol due to the CO2 uptake during soybean cultivation and the leaked methane in methanol production. For the other six categories, the production of biodiesel using ethanol has a better environmental performance over biodiesel from methanol. The emission of agrochemical and solvent play an importance role in these six categories. More agrochemical and solvent were discharged in biodiesel from methanol because in transterification using methanol and larger amount of soybean oil have to use in order to get same amount of biodiesel product (1000 kg).

The single score method was applied to identify the best option among biodiesel from methanol feedstock and ethanol feedstock. It was done by using global normalization and weighting factor based on ecotaxes. The result indicated that biodiesel from ethanol was more environmental friendly than biodiesel from methanol. It also showed that agricultural process was the main contributor, which contributed more than 90% of the total environmental load. Further developments in soybean cultivation as well as other processes are needed to make biodiesel production more environmental friendly.

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