

# Environmental Life Cycle Assessment of Palm oil- based Biofuel Production from Transesterification: Greenhouse Gas, Energy and Water Balances

Virin Kittithammavong, Noulkamol Arpornpong, Ampira Charoensaeng, and Sutha Khaodhiar

**Abstract**—Palm oil based biodiesel is a foremost alternative fuel widely distributed in Thailand and South East Asia. Transesterification with alkaline based catalysts is the most common process for converting vegetable oils into biodiesel. Water washing is a typically used method for biodiesel purification after transesterification reaction. Consequently, large volumes of a wastewater stream is generated and discharged into the environment. In order to satisfy water quality standards, treatment processes are then basically required, which result of an increase in overall GHG emissions. Biodiesel purification by distillation is one of the available technological options that require less direct water consumption than the conventional water-based purification. In this study, the biodiesel production from palm stearin combined with the distillation unit in the purification process was investigated through the environmental life cycle analysis of the product in terms of GHG emissions, energy and water consumption. The materials flow (cradle to gate approach) including oil palm cultivation, palm oil mill (palm oil extraction and crude palm oil refining), transportation and transesterification was analyzed and one liter of pure biodiesel was set as the functional unit.

The results show that the total GHG emissions, the energy and water consumption are 2.83 kgCO<sub>2</sub>e/L, 30.49 MJ/L and 23.64 m<sup>3</sup>/L, respectively. The palm oil mill stage produced the largest GHG emissions accounting for 59.56% of all emissions from the processes. For energy consumption, oil palm cultivation consumes the highest energy consumption, accounting for 45.36% of all energy use, and it is followed by transesterification (37.62%), transportation (9.18%) and palm oil mill and refining (7.85%). The total Net Energy Balance (NEB) is 95.72 MJ/L and the Net Energy Ratio (NER) is 4.14. In addition, the transesterification stage is divided into transesterification reaction, biodiesel purification, glycerol purification and methanol purification processes. The entire GHG emission of the transesterification stage is 0.52 kgCO<sub>2</sub>e/L and the energy consumption is 11.47 MJ/L. It is interesting to note that the water used in the biodiesel purification by the distillation method consumes less water (0.0043 L/L) than a conventional method. In

transesterification, most of the GHG emissions and energy consumption were contributed from raw materials preparation (i.e. methanol, catalyst). The results of this study will provide the insight of environmental performance through life cycle analysis for developing low carbon biodiesel technologies.

**Keywords**—Biodiesel, GHG emission, Life Cycle Assessment, Transesterification

## I. INTRODUCTION

**E**NERGY is a significant factor in the development of human civilization. To date the energy source is prominently derived from non-renewable fossil fuels. Large volumes of petroleum oils are used in various activities, especially transportation [1]. Consequently, the country that has scarce reserves of energy resources needs to import them from overseas. Thailand likewise has been importing petroleum based fuels for past few decades. Unfortunately, this trend is expected to dramatically soar. Regarding energy security policy, The Thailand Biodiesel Development Plan 2008-2022 has been established to promote palm oil production as well as the use of B5 and B10 as a renewable fuel for transportation.

Biofuel can be produced from triglyceride based oils such as vegetable oils, an animal fats and waste from cooking oils. Due to the fact that triglyceride oils have high viscosity, their viscosities need to be reduced before they are used in engines. A number of biofuel technologies have been developed to reduce the limitations of high viscosity in vegetable oils including direct blending, microemulsion, pyrolysis and transesterification [2], [3]. Transesterification or alcoholysis using an alkaline based catalyst is a common method in commercialized manufacturing. The advantages over other technologies are that it is easy to control, low cost and highly efficient [2]. In transesterification, natural oil or triglyceride reacts with alcohol and the catalyst to produce fatty acid methyl ester (FAME) or biodiesel as the main product and glycerol as the co-product. There are a four-step process in the transesterification process, which includes transesterification reaction, biodiesel purification, glycerol purification and alcohol purification. While biodiesel can be purified using various methods, e.g., water washing, distillation, membrane and ion exchange [4], distillation is a superior option for glycerol and alcohol purification.

Virin Kittithammavong is with the Department of Environmental Engineering, Chulalongkorn University, Thailand (e-mail: Kitt.Virin@gmail.com)

Noulkamol Arpornpong is with the International Postgraduate Program in Environmental Management, Chulalongkorn University, Thailand (e-mail: anoulkamol@gmail.com).

Ampira Charoensaeng is with the Petroleum and Petrochemical College, Chulalongkorn University, Thailand (e-mail: Ampira.C@chula.ac.th).

Sutha Khaodhiar is with the Department of Environmental Engineering, Chulalongkorn University, Thailand (e-mail: Sutha.K@chula.ac.th).

According to ISO 14040, life cycle assessment (LCA) is an analytical tool which compiles and evaluates inputs, outputs and potential environmental impacts of a production system throughout its life cycle. The steps of LCA include setting the goal and scope, gathering the life cycle data inventory, evaluating the impact assessment and interpreting the data. A number of LCA research studies associated with biodiesel production have been investigated in terms of greenhouse gas emissions and the energy balance throughout the life cycle starting from the palm oil cultivation and continuing to the biodiesel production.

In this study, we focused on palm oil based biodiesel production with distillation technology. The environmental impacts together with energy and water consumption were also compared to indicate the environmental burden of the technology.

## II. METHODOLOGY

### A. Goal and scope of research

The goal of this study was to assess greenhouse gas emissions, and the energy and water balances of the palm oil biodiesel life cycle. The system boundary of biodiesel production was scoped based on cradle-to-gate, which was divided into four main parts including oil palm cultivation, palm oil mill (palm oil extraction and crude palm oil refining), and transesterification. In addition, transesterification was subdivided into four main processes including transesterification reaction, biodiesel purification, glycerol purification and alcohol purification. The functional unit (FU) of this study was defined as 1 liter of biodiesel. Fig.1 presents the system boundary and all the steps of the processes of this study. The inventory data used in this study were gathered from both primary and secondary data sources.

### B. Oil palm cultivation

More than 70 percent of oil palm is widely cultivated in the

southern part of Thailand because of the suitable topography and weather conditions, especially in the provinces of Krabi, Chumporn and Suratthani [5], [6]. The raw materials of this stage included seeds, N-fertilizer,  $P_2O_5$  fertilizer,  $K_2O$  fertilizer, glyphosate and paraquat herbicides. All inventory data from cultivation and harvesting were collected from the literature surveyed. Transportation of fertilizers was estimated by a one-way, full load with the distance of about 865 km [7]. The major product output was fresh fruit bunch (FFB). The average palm oil yield is 16.5 tons of FFB per hectare per year and the average lifetime planting is 25 years [8]. Note that, the environmental impact from changes in the land used was not taken into account in this study.

### C. Palm oil mill

After harvesting, FFB are transported to palm oil mills within 24 hours to maintain the oil quality. Thus, palm oil mills are usually located near plantation areas [7]. All data used in this stage were collected from secondary data sources [5], [8], [9]. The material inputs were water, electricity, diesel and chemicals including kaolin for the separation of the palm kernel from the shell, polyaluminium chloride, anionic polymer, hydrochloric acid and sodium hydroxide for the water treatment. Typically, an anaerobic pond is a common wastewater treatment system constructed in palm oil processing factories. The solid waste generated in this process is the empty fruit bunch (EFB) and the decanter cake. The main product is crude palm oil (CPO). The co-products are palm kernel, shell and fiber. Then CPO is transported to the refining process, where the neat palm oil is fractionated into palm olein and palm stearin. The total yield of palm stearin is equivalent to 0.29 kg/kgCPO [7]. In this study, we assumed that the CPO refining process used energy in the form of electricity only.

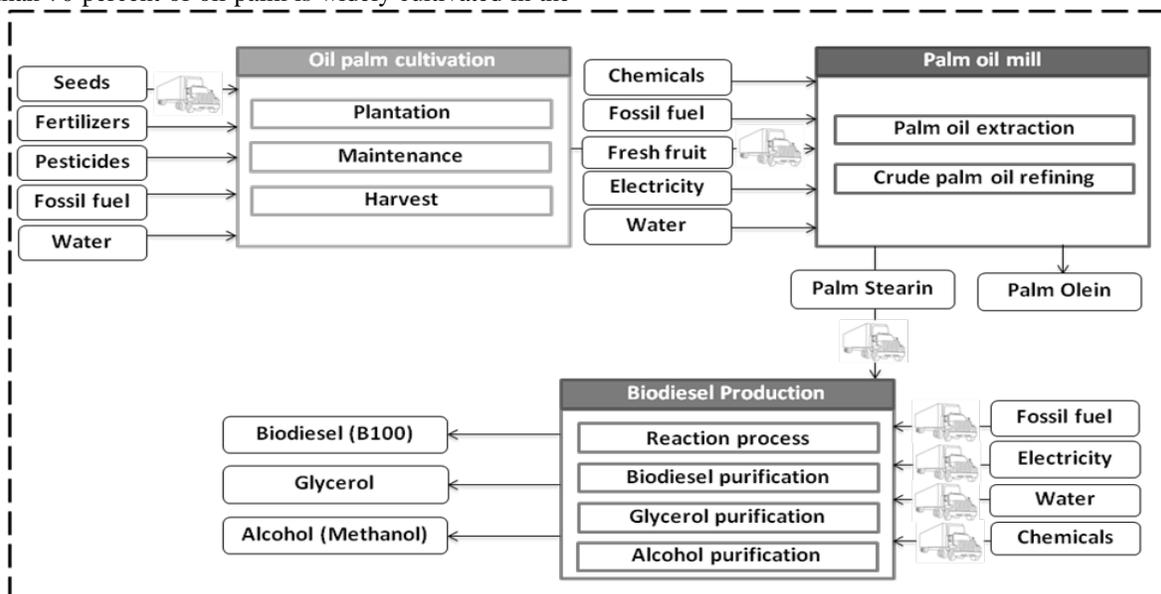


Fig. 1 System boundary of the study

#### D. Transesterification Stage

The inventory data of the transesterification stage were collected from a commercialized biodiesel manufacturer with 200,000 liters production capacity per day. Fig.2 shows the production processes including the transesterification reaction process, biodiesel purification, glycerol purification and alcohol purification. In the sampling site, the distillation systems are used for purifying each chemical. As a consequence, there is no additional wastewater system required for treating large amounts of oil contaminated wastewater. The raw material inputs were palm stearin, methanol (MeOH), sodium methoxide (or sodium methylate or NaOCH<sub>3</sub>) as the alkaline based catalyst, kerobit as the anti-oxidant for adjusting biodiesel quality, activated carbon, phosphoric acid (H<sub>3</sub>PO<sub>4</sub>) for glycerol neutralization, sodium chloride (NaCl) for demineralization in water treatment, electricity (from EGAT: Electricity Generating Authority of Thailand), tap water and fuel oil. The main product of this process is neat biodiesel (B100) and the co-products are pure glycerol and methanol. The waste produced from glycerol and methanol purification is sold to other manufacturers. Thus, the impact from waste disposal was not taken into the assumption. Palm stearin, MeOH, activated carbon, NaCl and fuel oil are transported by 10-wheel trucks with the distance of 10, 80, 80, 10 and 12 km, respectively. NaOCH<sub>3</sub> and kerobit are imported from China by ship (one-way around 4,020 km) and transported to factory by truck (80 km). H<sub>3</sub>PO<sub>4</sub> was imported from Germany by ship (one-way distance of 17,282 km) and transported by truck (80 km).

#### E. Transportation

In this study, the transportation stage only accounted for the FFB and palm stearin transportation because the other raw materials such as fertilizers and chemicals were allocated in each stage of the raw material acquisition. Transportation of FFB, which was collected from secondary data, was transported by truck with the distance of 50-70 km for a one-way, and 100-140 km for a round trip [7]. However, palm

stearin delivery was collected from primary data by direct inquiry, from the palm oil mill to the production plant, which is about 10 km (round-trip 20 km).

#### F. Greenhouse gas analysis

According to Kyoto protocol, the six main greenhouse gases are carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), sulphur hexafluoride (SF<sub>6</sub>), per fluorocarbons (PFC's) and hydro fluorocarbons (HFC's). In this study, we accounted for only three types of greenhouse gases including CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O because these are the most prevalent gases found in biodiesel production. The GHG emissions of product as shown in equation (1) can be calculated from raw material acquisition, production, transportation and pollution in unit kg CO<sub>2</sub> equivalent per functional unit, which is one liter biodiesel. The GHG emissions from production can be calculated from equation (2). The GHG emissions from pollution or waste are release during the manufacturing process. An example is wastewater. The GHG emissions of each section are calculated based on equation (3) by multiplying between activity data and the emission factor. All activity data are listed in Table I.

$$E_{\text{GHG,product}} = E_{\text{GHG,raw material acquisition}} + E_{\text{GHG,production}} + E_{\text{GHG,transportation}} + E_{\text{GHG,pollution}} \quad (1)$$

$$E_{\text{production}} = E_{\text{fuel,acquisition}} + E_{\text{fuel,combustion}} + E_{\text{water}} + E_{\text{electricity}} \quad (2)$$

$$\text{GHG emissions (kgCO}_2\text{/FU)} = \text{Activity data} \times \text{Emission factor} \quad (3)$$

#### G. Energy balance analysis

Energy consumption was calculated from raw material acquisition, production and transportation. The result of each section was described in MJ/L B100 unit by multiplying the activity data and energy factor, as shown in Table I. Energy outputs were the results of the multiplying activity data (kg/L) by calorific value (CV) or lower heating value (LHV).

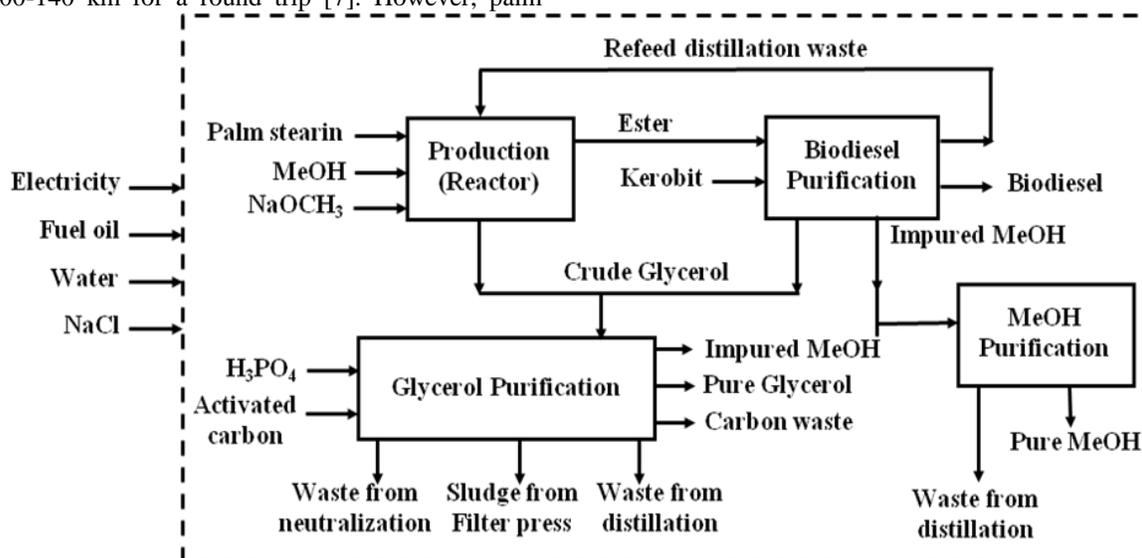


Fig. 2 Flow chart of biodiesel plant

TABLE I  
INVENTORY DATA FOR CALCULATION

Stages	Amount (kg/L B100)	Stages	Amount (kg/L B100)
<b>1 Oil palm cultivation</b>		<b>3.2 Biodiesel purification process</b>	
Seed	0.16418	Kerobit	0.00000000212
N fertilizer	0.13844	NaCl (water treatment) (L/L)*	0.00202
P <sub>2</sub> O <sub>5</sub> fertilizer	0.03504	Electricity (kWh/L)*	0.01582
K <sub>2</sub> O fertilizer	0.26889	Water	0.00141
Glyphosate	0.00467	Fuel oil (L/L)*	0.03299
Paraquat	0.00168	Fuel oil (combustion) (L/L)*	0.03299
Diesel	0.00503	Diesel (kerobit one-way ship & two-way truck) (km)*	17441.8
Diesel (combustion)	0.00503	Diesel (truck NaCl round-trip) (km)*	20.0000
Diesel (truck fertilizers one-way) (km)*	865.000	Diesel (truck fuel oil round-trip) (km)*	24.0000
<b>2 Palm oil mill</b>		<b>3.3 Glycerol purification process</b>	
Kaolin (separation PK from shell)	0.03472	H <sub>3</sub> PO <sub>4</sub> (neutralization)	0.00342
Polyaluminium chloride (water treatment)	0.00098	Activated carbon	0.00020
Anionic polymer (water treatment)	0.00146	NaCl (water treatment) (L/L)*	0.00202
HCl (water treatment)	0.00456	Electricity (kWh/L)*	0.02003
NaOH (water treatment)	0.00427	Water	0.00245
Electricity (CPO extraction) (kWh/L)*	0.17073	Fuel oil (L/L)*	0.01885
Water (m <sup>3</sup> /L)*	0.01881	Fuel oil (combustion) (L/L)*	0.01885
Diesel	0.00880	Diesel (H <sub>3</sub> PO <sub>4</sub> one-way ship & two-way truck) (km)*	4180.00
Diesel (combustion)	0.00880	Diesel (truck activated carbon round-trip) (km)*	160.000
Electricity (CPO refining) (kWh/L)*	0.00405	Diesel (truck NaCl round-trip) (km)*	20.0000
Wastewater (m <sup>3</sup> /L)*	0.01489	Diesel (truck fuel oil round-trip) (km)*	24.0000
<b>3 Transesterification plant</b>		<b>3.4 Methanol purification process</b>	
<b>3.1 Reaction process</b>		NaCl (water treatment) (L/L)*	0.00067
MeOH	0.18659	Electricity (kWh/L)*	0.00316
NaOCH <sub>3</sub>	0.00589	Water	0.00047
Refeed distillation waste	0.07688	Fuel oil (L/L)*	0.00766
Electricity (kWh/L)*	0.00685	Fuel oil (combustion) (L/L)*	0.00766
Fuel oil (L/L)*	0.00707	Diesel (truck NaCl round-trip) (km)*	20.0000
Fuel oil (combustion) (L/L)*	0.00707	Diesel (truck fuel oil round-trip) (km)*	24.0000
Diesel (truck MeOH round-trip) (km)*	160.000	<b>4 Transportation</b>	
Diesel (NaOCH <sub>3</sub> one-way ship & two-way truck) (km)*	4180.00	Diesel (truck FFB round-trip) (km)*	120.000
Diesel (truck fuel oil round-trip) (km)*	24.0000	Diesel (truck palm stearin round-trip) (km)*	20.0000

#### H. Water balance analysis

The water use in the transesterification plant was estimated from two categories; on-site or the direct water consumption in the production of biodiesel and water footprint. According to the water footprint assessment guideline [10], the water footprint is an indicator of the freshwater used to produce the product along supply chains. Based on the Water Footprint Network (WFN), the water footprint is the summation of green, blue and grey water footprints. Green water refers to rainwater in so far as not become run-off water. Blue water refers to surface and groundwater. Grey water refers to the

volume of freshwater that is required to dilute the wastewater to existing water quality standards. Each water use assumption was calculated from the results of multiplying the activity data (Table I) by the water factor. A few studies have investigated the water footprint analysis of cultivation [11], [12], [13]. They reported that the water footprint of oil palm cultivation for biodiesel in the southern of Thailand, divided into green water, blue water and grey water, were 750, 138 and 511 m<sup>3</sup>/ton FFB, respectively [11]. However, based on a quantity of FFB, we can estimate the volume of water used in oil palm cultivation.

### III. RESULTS AND DISCUSSION

#### A. GHG emissions

The total GHG emissions of the biodiesel production were 2.83 kgCO<sub>2</sub>e/L. Table II and Fig.3 summarize the GHG emissions from each process. As shown by the pie chart in Fig.3, the palm oil mill is a primary contributor accounting for more than 50 percent of total GHG emissions, and it is followed by oil palm cultivation (18.99%), biodiesel production (18.22%) and transportation. This is because methane gas (CH<sub>4</sub>) from the wastewater treatment in the palm oil mill is released into the atmosphere, which is 25 times stronger than CO<sub>2</sub> [15]. The GHG emissions from the cultivation stage were slightly higher than those of the transesterification stage. This is due to the fact that the fertilizer and pesticide acquisitions have very high emission factors, especially paraquat herbicide (8.09 kgCO<sub>2</sub>/kg) [14].

The transesterification stage has a significant impact on GHG, accounting for 0.52 kgCO<sub>2</sub>/L. Fig.4 illustrates GHG emissions from each process during the transesterification stage. However, the average GHG emission of biodiesel production reported by the TGO database [14] is 1,087 kgCO<sub>2</sub>e/ton B100 or 0.9457 kgCO<sub>2</sub>/L B100. This value is three times lower than the GHG emissions obtained from this study. The reason may be because the environmental impact from palm stearin production as the raw material is higher than that of CPO.

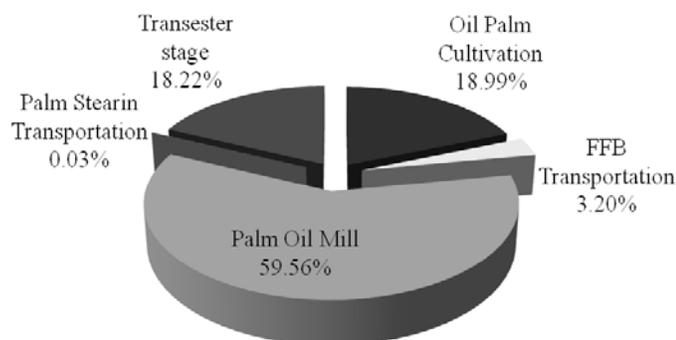


Fig. 3 GHG emissions of overall stages

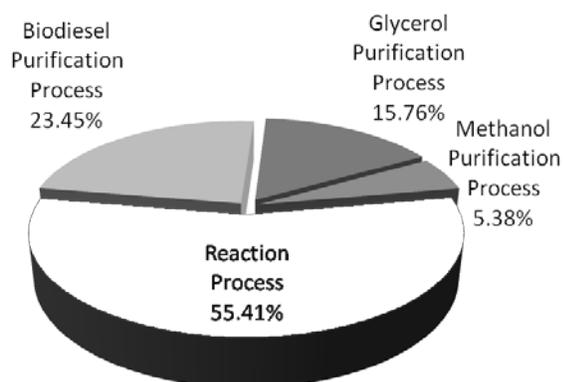


Fig. 4 GHG emissions of transesterification stage

TABLE II  
OVERALL STAGE RESULTS

Stage	GHG emissions (kgCO <sub>2</sub> /L)	Energy balance (MJ/L)	Water balance (L/L)
1 Oil palm cultivation	0.53804	13.82979	23561.87194
2 Palm oil mill	1.68715	2.39319	65.98209
3 Transesterification			
Reaction process	0.28602	7.96541	5.46021
Biodiesel purification	0.12102	1.85765	3.03731
Glycerol purification	0.08134	1.22024	3.09654
Methanol purification	0.02779	0.42648	0.64789
4 Transportation			
FFB	0.09059	2.77558	2.91734
Palm stearin	0.00078	0.02376	0.02498
5 Overall summation	2.83273	30.49212	23643.03832

TABLE III  
ENERGY OUTPUT

Material Outputs	Quantity (kg/L)	Energy content (MJ/kg)	Source	Energy output (MJ/L)
Palm kernel	1.02832	17	[5], CV	17.48
Fiber	2.03479	11.4	[7], LHV	23.20
Shell	1.06809	18.46	[5], CV	19.72
EFB	4.14310	7.24	[7], LHV	30.00
Biodiesel	0.87000	38.07	[5], CV	33.12
Pure glycerol	0.04581	19	[5], CV	0.87
Pure methanol	0.09127	20.094	[17], LHV	1.83
Total				126.22

#### B. Energy balance

The total energy consumption of biodiesel production was 30.49 MJ/L. In Fig.5, the highest energy consumption associated with the oil palm cultivation stage accounted for 45.36% of all energy consumption. This is because the acquisition of fertilizers and pesticides consumes a lot of energy. The palm oil mill stage exhibited the lowest energy consumption, accounting for 7.85% of all energy consumption. This is due to the fact that solid wastes can be completely utilized. For instance, fiber residues are used for generating electricity or steam.

The transesterification stage consumed approximately 37% of the total energy (11.47 MJ/L). It was subdivided into the reaction process (69.44%), biodiesel purification (16.20%), glycerol purification (10.64%) and methanol purification (3.72%), as shown in Fig.6. It can be observed from the chart that the reaction process had the highest energy consumption. In this step, energy in the form of hot steam is intensively required in the distillation column to purify crude biodiesel. In comparison, the biodiesel and glycerol purification consumed more energy than methanol purification. When considering the direct energy consumption used in the transesterification stage

through the cradle to gate approach, the distillation method consumed more energy than did the conventional water washing technology.

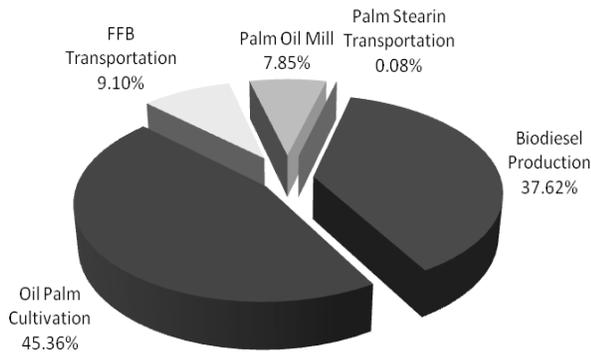


Fig. 5 Energy consumption of overall stages

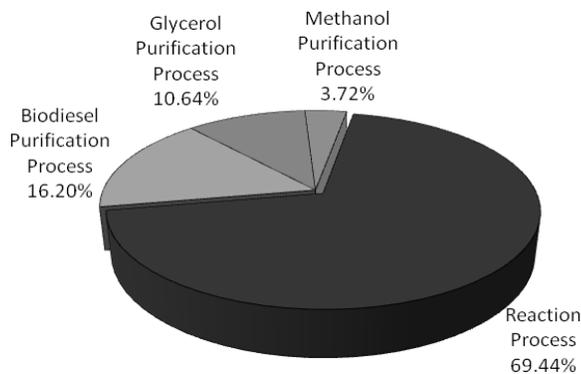


Fig. 6 Energy consumption of transesterification stage

The total energy input was 30.49 MJ/L (Table II), whereas the total energy output was 126.22 MJ/L as shown in Table III. Note that the NEB was 95.72 MJ/L and NER was 4.14, which are higher than those reported in other previous works [5], [7]. The energy outputs were calculated based on possible utilization in this study, which included palm kernel, fiber, empty fruit bunch, shell, pure methanol, pure glycerol and biodiesel. For instance, EFB can be used for mushroom cultivation and shells can be used as raw material in activated carbon production [7].

The energy output of biodiesel described in terms of NEB and NER were equal to 2.63 MJ/L and 1.09, respectively. These figures are lower when compared with the results from previous studies [5], [7], [16], which was because the transesterification stage could collect data more thoroughly. Also, the energy output was still greater than the energy input because it was higher than diesel (NEB -8.3 MJ/kg and NER 0.84) [7].

### C. Water balance

The total water consumption of the biodiesel production was 23.64 m<sup>3</sup>/L, as shown in Table II. The largest water consumption (99.66%) was associated with oil palm cultivation and it was followed by palm oil mill, biodiesel

production and transportation, respectively. The palm oil mill stage consumed water more than the transesterification stage because water was used for sterilization, oil clarification and oil purification in the palm oil mill [8]. Based on water footprint calculations of all the stages of the biodiesel production, it was found that the total water consumption divided into sub-categories, green water, blue water and grey water, were 53.43%, 10.16% and 36.41%. The green water had the highest portion, indicating that the primary source of the water was rainwater, especially in oil palm cultivation. The transesterification stage consumed water of 12.24 L/L, which was divided into the reaction process (44.60%), biodiesel purification (24.81%), glycerol purification (25.30%) and methanol purification (5.29%), see in Fig.7.

In comparison, the transesterification stage with the distillation process consumed more water than did the water washing based biodiesel plant. Based on the assumption, which included water used in raw material preparation (indirect water), the average water footprint value of electricity acquisition was 7.8 L green water, 105 L blue water and 0.5 L grey water for one kWh [18]. Water was used as the main resource to produce electricity. Thus, biodiesel plants with the distillation method used more electricity than did the water washing method. Other significant indirect water was tap water acquisition. The water consumption for tap water production was 2.42 L water used per L tap water [19]. Therefore the direct water consumption of this study was multiplied.

When comparing within on-site water consumption, the biodiesel purification with distillation consumed 24 times less water than did the water washing technology. In this study, the biodiesel plant (Transesterification stage) consumed direct water at 0.0043 L/L (not multiplying by the water factor of the tap water).

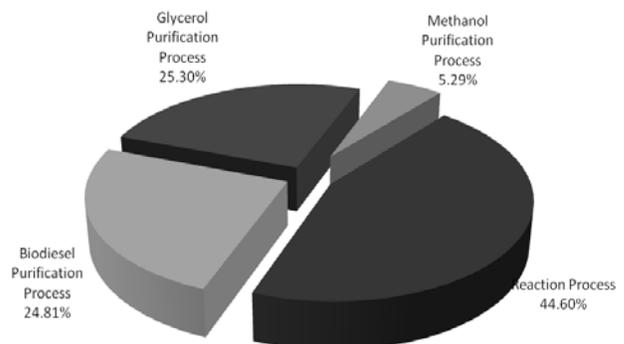


Fig. 7 Water balance of transesterification stage

## IV. CONCLUSIONS

The life cycle GHG emissions of biodiesel production were 2.83 kgCO<sub>2</sub>e/L, and the transesterification stage was 0.52 kgCO<sub>2</sub>e/L, accounting for 18.22% of the GHG emissions. The total energy consumption was 30.49 MJ/L. This is higher than in other studies because the distillation method used for biodiesel purification consumes a significant amount of energy. The biodiesel production with distillation requires a large amount of energy for heating of the distillation column

and the cooling product, whereas the conventional plant (water washing) uses energy in biodiesel purification for heating water only. The NEB and NER of biodiesel production (without co-product) were 2.63 MJ/L and 1.09, respectively. The total water consumption through the whole biodiesel production life cycle was 23.64 m<sup>3</sup>/L. For the transesterification stage, the water consumption was 0.012 m<sup>3</sup>/L (equal to 0.05% of the total consumption), which was higher than that of the water washing purification method. This is due to the indirect water contributed to the water used in electricity production partly being derived from hydropower. Note that the distillation method consumed less water, but it was an energy intensive technology. This leads to significantly GHG emissions contributing to the environment when compared with the water washing method. These two methods have different pros and cons, so economics may be used as an alternative tool to choose the technology for biodiesel production. For instance, if a country is full of energy resources and lacks water, the distillation method is suitable for biodiesel production.

#### V. ACKNOWLEDGMENT

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