Environmental load assessment for an integrated design of microalgae system of palm oil mill in Indonesia

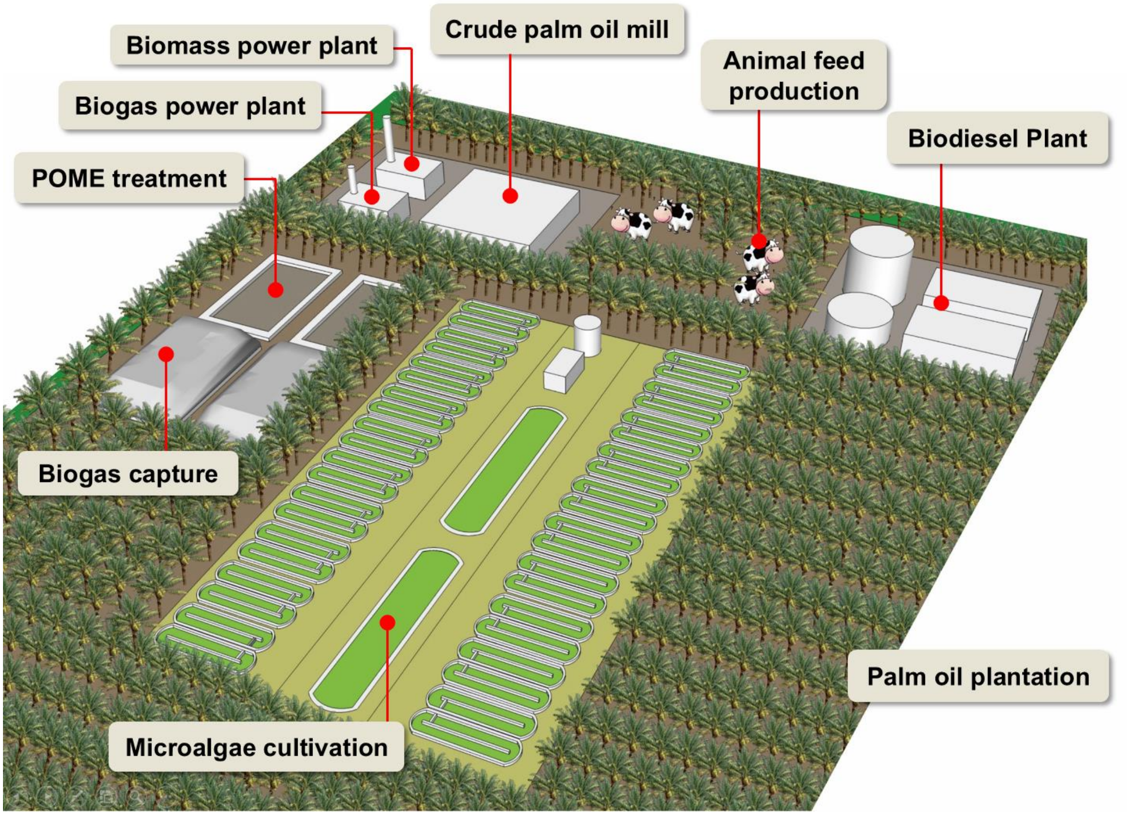
Nugroho Adi Sasongko [a,b], Ryozo Noguchi [c*], Tofael Ahamed [c]

[a] *Graduate School of Life and Environmental Sciences, University of Tsukuba,*
1-1-1 Tennodai, Tsukuba, Ibaraki, 305-8572, Japan
[b] *Agency for the Assessment and Application of Technology (BPPT), 10340, Indonesia*
[c] *Faculty of Life and Environmental Sciences, University of Tsukuba,*
1-1-1 Tennodai, Tsukuba, Ibaraki, 305-8572, Japan

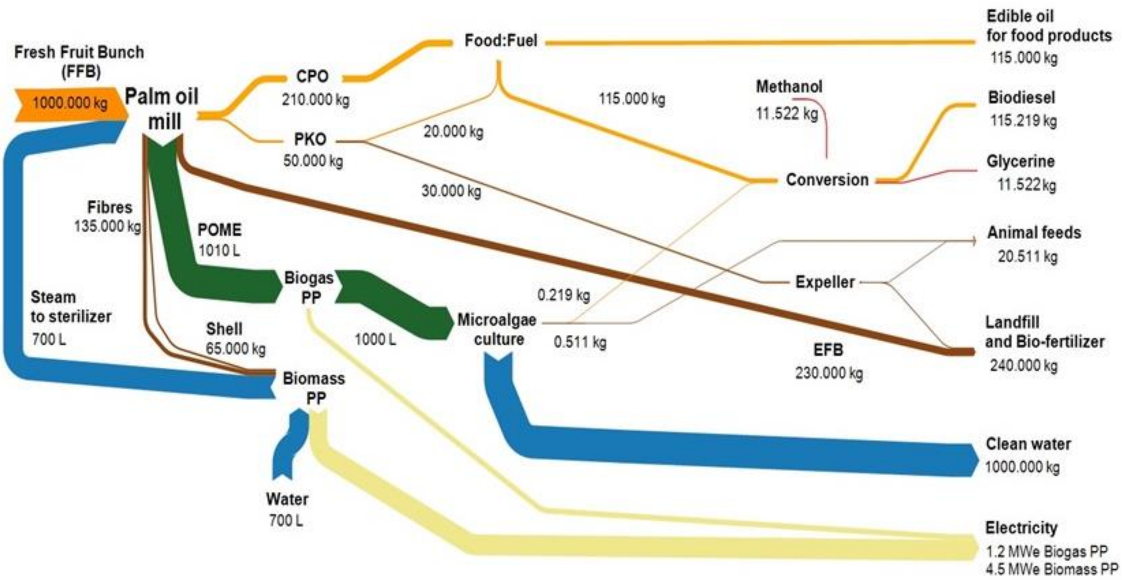
Highlights

- An environmental load assessment for a proposed microalgae culture was conducted
- Palm oil mill effluent and flue gases were used as alternative nutrient sources
- The proposed system increased the energy-profit ratio and lessen GHG emission
- Co-products of animal feed and bio-fertilizer was ensured from defatted biomass

Graphical Abstract



Additional/alternative of graphical abstract:



Abstract

The environmental load of continuous bioenergy production from palm oil (*Elaeis guineensis*) included with a proposed 10 ha of microalgae production system were assessed to be implemented in Indonesia. Material and energy balances, greenhouse gas (GHG) emission, nutrient requirement and also water scarcity during bioenergy production cycle were evaluated. The integrated system was developed for 60 tons h^{-1} of fresh fruit bunch (FFB) processing capacity of a conventional mill. Aggregate of energy-profit ratio from the proposed system was 5.20, which indicates a positive balance. The total water footprint for each palm oil and microalgae cultivation was 3.18 and 2.85 m^3 kg^{-1} of biodiesel production, respectively. Microalgae mix-culture has the potential to treat organic compounds from palm oil mill effluent (POME) and combined with flue gases from biomass and biogas power plant as the alternative nutrient sources contributed to net-reduction of GHG emission for 158.8 tons ha^{-1} of microalgae culture, annually. The integrated system produced 26,471 tons of biodiesel that included 223 tons from microalgae and contribute to 39.90% of total GHG emission reduction from diesel fuel substitute. Additional co-product of 520.33 tons $year^{-1}$ of animal feed from defatted biomass also possible to be produced and have potential for environmental benefits.

Keywords

biofuel crops, energy balance, environmental load, integrated system, life cycle assessment

----

＊Corresponding author: Tel./fax: +81 (0)29-853-4697

e-mail address: noguchi.ryozo.gm@u.tsukuba.ac.jp

Nomenclature

i	name of sub-stage
j	process name
n	material or product name
e_{stage}	emissions of product for each stage [g-CO_2eq MJ^{-1}]
CV	calorific value [MJ kg^{-1}]
$EC_{i,j}$	process j energy consumption during sub-stage i [MJ]
E_{prod}	total energy that can be produced, including co-products, in each stage [MJ]
$M_{i,n}$	material n consumption during sub-stage i [kg]
PE_j	life cycle primary fossil energy use for process j energy production [MJ MJ^{-1}]
PE_n	life cycle primary fossil energy use for material n production [MJ kg^{-1}]
WF	water footprint includes three components: green, blue, and gray [m^3-water kg^{-1}-product]
t·km	ton kilometer
MJ	mega joule
TJ	terra joule
AS	ammonium sulfate $(NH_4)_2SO_4$
BDF	biodiesel fuel
CED	cumulative energy demand
CO_2eq	carbon dioxide equivalent
DAP	diamonium phosphate $(NH_4)_2HPO_4$
dw	dry weight
EFB	empty fruit bunch
EPR	energy profit ratio
FFB	fresh fruit bunch
GHG	greenhouse gas(es)
GWP	global warming potential
HTL	hydrothermal liquefaction
IPCC	intergovernmental panel on climate change
ISO	international standard organization
LCA	life cycle assessment
LCI	life cycle inventory
LUC	land use change
N	nitrogen fertilizer
ND	no data
NPK	nitrogen phosphorus potassium
PBR	photo bio-reactor
PKO	palm kernel oil
PP	power plant
PO	palm oil
POME	palm oil mill effluent
S	sulfur fertilizer
SP-36	superphosphate, with 36% P_2O_5
SSP	single superphosphate
TOC	total organic carbon
TSP	triple superphosphate
H_3PO_4	phosphoric acid
K_2O	potassium oxide
K_2SO_4	potassium sulfate
KCl	potassium chloride
NaOH	sodium hydroxide
P_2O_5	phosphorus pentoxide

1. Introduction

There are few feedstocks that dominate bioenergy production, and their vast cultivation of feedstock can contribute to affect the environmental load, including the energy requirements, CO_2eq emissions, water scarcity, and fertilizer utilization. Increasing production of biofuel crops boosts fertilizer and water consumption **[1, 2]**. World nitrogen-based fertilizer consumption for biofuel production was estimated to be 3.4 million tons of nitrogen for the 2013/2014 growing period and corresponds roughly to 3.1% of global nitrogen consumption **[3]**. Nitrogen fertilizer has the largest embedded energy compared to other fertilizers, requiring about five times more energy to produce per ton than phosphorous and potassium fertilizers and typically accounting for approximately 50-65% of on-farm energy use for high yield crops **[3, 4]**. Based on data from the Association of Indonesia Fertilizer Producers (AIFP), the dominant fertilizers produced and used in Indonesia were urea, superphosphate (SP; 36% P_2O_5), ammonium sulfate (AS; 21% N and 24% S), and NPK (18% nitrogen, 22% phosphorus, 17% potassium) **[5]**. Nutrient use can have a significant impact on the energy balance in an agricultural system, thus information on the required amount could reveal both under- and over- estimation of energy inputs. **Fig. 1** shows trends in urea production and consumption in Indonesia from 1960 to 2016. Detailed historical data of fertilizer demand for food and estate crops was well recorded starting in 2007. Urea fertilizer demand for estate crops increased, while for food crops it decreased or was stagnant. In 2016, urea demand for estate crops (including palm oil) increased by up to 15%. The increase in use of crude palm oil (CPO) as an international commodity increased production, and the subsequent expansion of high-yield plantations increased fertilizer consumption.

Water scarcity has increased with the rise in biofuel used to fulfill the new requirements. Water scarcity from biofuel production is the ratio of the total volumetric water footprint (WF) in the catchment to the water availability used for the production cycle, measured for the entire supply chain **[6]**. The total WF is equal to the aggregate volumetric water footprint of all activities in the catchment **[7]**. In most places, the water consumption of crops could be a resource barrier for biofuel production, and could potentially limit the scalability and environmental sustainability of large-scale biofuel systems. Analysis of the water scarcity related to a biodiesel production chain was therefore addressed in this research by the WF approach. **Fig. 2** summarizes the WF of several biofuel crops **[1, 8-11]**, including the results from our field measurement. The green WF refers to the total rainwater lost due to evapotranspiration (from fields and plantations), including the water incorporated into the harvested crops. Meanwhile, the blue WF indicates the volume of surface and groundwater consumed as a result of biomass production and service **[6]**. Consumption refers to the volume of freshwater used and then evaporated or incorporated into a product. It also includes water diverts from surface water or groundwater in the plantation area, or the amount of water takes from groundwater or surface water sources that does not return to the catchment from which it is withdrawn. The grey WF of a product is an indicator of freshwater pollution that can be associated with the production of a product through its entire supply chain. The grey WF is also defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. In fact, the geographical location, soil condition, and crop species are the primary factors affecting the specific WF. Thus, in some parts of the world, the environmental load of biofuel crops can be lower than in others.

As the new regulation from the Ministry of Energy and Mineral Resources of Indonesia (2015)**[12]** promotes mandatory biodiesel utilization, with a 15% biodiesel blend for commercial, industrial, and transportation sectors, and a 25% blend for power plants, the government also tries to find alternatives to balance the demand and supply of biodiesel feedstock. Palm oil and microalgae are attractive for biodiesel production because of high biomass and lipid productivity per square area which exceeds the other biofuel crops **[13]**. These crops may provide a viable alternative to replace a significant portion of fossil fuels used today with a smaller environmental burden compared to other biofuel crops **[14-17]**. During the production of CPO, mills release an abundant amount of solid waste and wastewater. This agro-industrial effluent is heavily polluted with biodegradable organic material and needs treatment prior to discharge. However in a mixotrophic condition, microalgae can grow well in wastewater which has sufficient nutrients, placing no additional pressure on freshwater and fertilizer supplies **[18, 19]**. POME from anaerobic ponds still contain a high concentration of ammonium and phosphorus approximately 125.1 mg L^{-1} of NH_4^+-N and 68.40 mg L^{-1} of PO_4^-P and might varies depend on the effluent treatment and season **[13]**. This effluent is a valuable bio-resource for microalgae cultivation. In addition to diminish the environmental problem, a cleaner water and also potential biomass production for further bio-products can be able to obtain. However, major transformative breakthroughs are required to make microalgae biofuels viable both energetically and economically **[20, 21]**.

Attached microalgae production system to the existing palm oil plantation/mill might obtain additional benefits compared to the individual crops being cultivated separately in different locations. **Fig. 3** illustrates a scheme of the proposed synergized system. This model integrates agricultural waste management to ensure optimum bio-resources utilization as well as environmental sustainability for the existing palm oil plantation. The microalgae system was introduced to this model to achieve resource efficient and optimum bio-resource utilization. The proposed integrated of microalgae culture have two major functions: 1) Lowering polluted water and GHG emission by nutrients recycling (resources recovery); 2) Producing more biomass for bio-products, such as animal feed, biofuel and biofertilizer. In order to address these issues, this research was conducted to confirm the critical environmental load of the proposed integrated system of palm oil and microalgae using the life cycle assessment (LCA) method.

2. Materials and Methods

2.1 Scheme of field measurement and simulation

This research was a case study based on average field measurement data from a major palm oil plantation located in Indonesia (Riau province, Sumatra island). Palm oil-based bioenergy data was obtained from a plantation and mill during 2013-2014. As summarized in **Table 1**, Riau province is located in the equatorial region, which has an upper seasonal mean temperature of 27^{o}C, average solar radiation of 17 MJ m^{-2} d^{-1}, average precipitation 2,870 mm $year^{-1}$, and evapotranspiration 1,460 mm $year^{-1}$, based on data from the local meteorology station nearby to the palm oil mill. The palm oil mill is located inside a 10,630 ha palm oil plantation and has an average processing capacity of 60 ton-FFB h^{-1}. We assumed that 50% of CPO used as feedstock for biodiesel production. Meanwhile, another 50% are dedicated for edible oil production for food and other oleo-chemical industries.

In the past, approximately 89.20% of the area was arable land and 10.80% was peat soil. However, the selected area has been planted for more than 40 years, thus the carbon payback time was assumed already reached **[22, 23]**. The expansion of plantation has considered using degraded-land, avoiding rain-forest conversion and the management has implemented environmental optimization of the palm oil plantation practice and processing facilities. Moreover, as the comprehensive analysis on the previous and future expansion of land use is still on going, the CO_2eq footprint analysis in this study was limited only to the routine cultivation and existing processing mill.

A prospective analysis has been performed for energy, GHG emission and water balances of POME treatment integrated with a microalgae production system. The Carbon, Nitrogen and Phosphorus (CNP) elements are the main ingredients of wastewater and essential nutrients for microalgae growth. To investigate microalgae-based biofuel production, a previous study of an integrated plantation model was used **[13]**. The microalgae culture, biomass productivity and nutrients ratio were adjusted also based on the selected previous research **[24-26]**. Native species of mixotrophic microalgae (*Chlorella sp.* and *Scenedesmus sp.*) were cultivated directly using POME after anaerobic digester. A stabilization pond was utilized to control the chemical composition in the POME to be suitable for microalgae growth in an existing facility. All parameters were assumed in a stable and steady state condition. A 10 ha scaled-up of mixed culture was simulated by quantifying the material and energy balances of the on-site production cycle. Experiment results from microalgae culture further combined with known downstream processes to design a large scale model. Cultivation ponds were assumed co-located in a palm oil mill, integrated with POME treatment and flue gases from biomass and biogas power plants as alternative medium and nutrients supplies. The average of microalgae biomass cell density can reach up to 0.73 g L^{-1} **[24]** with lipid productivity was reported range between 15 – 41 mg $L^{-1}d^{-1}$ or approximately 20-43%dw of biomass **[13, 24]**. As a comparison, this daily biomass productivity was confirmed in some references, reported ranged from 15.00 to 30.00 g $m^{-2}d^{-1}$ in open pond cultivation with potential annual production is up to 80 tons of biomass ha^{-1}year^{-1} **[25-27].** Our preliminary experiment results also confirmed these potential biomass and lipid productivities, and were used as the initial information in our integrated LCA analysis.

2.2 LCA framework and inventory analysis

International Organization for Standardization **-** ISO 14044:2006 has been used for life cycle assessment (LCA) as a technique to assess complex environmental impacts associated with all the stages of a product`s life, from cradle-to-grave (eco-balance) **[30]**. In addition, the International Panel on Climate Change (IPCC) characterization factors have been employed to analyze the global warming potential (GWP) of air emissions **[31]**. The GWP was assessed based on a 100-year time horizon for the environmental impacts of 1, 25, and 298, associated with carbon dioxide, methane, and nitrous oxide, respectively. Furthermore, this research likewise comprehensively analyzed the input-output balance, starting from the upstream process (cultivation stage), to the harvest/extraction stages, and finally the downstream process (conversion stage), which is known as a cradle-to-gate framework. SIMAPRO 8.1.1® software (PRé Consultants B.V.) coupled with Ecoinvent database 3.1® were used to calculate complex energy and material balances, including environmental inventories. The entire boundary condition for LCA in this research is presented in **Fig. 4**. The life cycle inventory (LCI) was conducted for each stages. The LCA for a palm oil plantation was calculated using a non-burn land clearing technique as referred from **[32-34]**.

The Cumulative Energy Demand (CED) method was used by including the energy input or consumption from three primary categories: 1) as electrical or power consumption, 2) energy in the form of heating, and 3) energy embedded in material product consumption. Currently, 52% of generated electricity in Indonesia supplied from coal-fired power plants **[35]**, which give average emission factor of 757.5 gCO_2eq kWh^{-1} **[36]**. As the off-grid biomass and biogas power plants were assumed as the main power source for equipment and facilities, thus potentially contribute to lower GHG emission by reducing dependency on electricity from national grid. Solid wastes (shell and fiber) were utilized for steam and power generation inside the mill, while methane from the POME anaerobic pond was supplied to the biogas power plant. Influence of worker activity and transport of materials was excluded as it was assumed as a co-location. Materials and energy associated with the construction of any infrastructure were not taken into account. The transesterification process was considered for the conversion of bio-crude to biodiesel, both for palm oil and microalgae. The biodiesel conversion data of CPO and microalgae was derived from laboratory experiment. Other co-products such as palm kernel cake and defatted microalgae biomass were assessed as the potential source of animal feed and bio-fertilizer.

The water source or system and chemicals used from domestic market places were analyzed in order to obtain a comprehensive evaluation. The *Hoekstra* method **[37]** was chosen to calculate water scarcity, where the WF from used materials and energy was taken from techno-sphere inventories. In addition, the average rainfall and evaporation for the selected location was calculated based on data from the local meteorological station.

2.3 Empirical formulation

To estimate the availability of important nutrients, the average of organic composition in POME was measured continuously throughout five years (2009 – 2014). The effluent has an average NH_4^+-N 125.1 mg L^{-1} and can reach up to 269.58 mg L^{-1} after anaerobic pond **[13]**. Meanwhile, to estimate total organic carbon (TOC), we used a process engineering software SUPERPRO DESIGNER® to calculate carbon ratio based on the available organic compounds in POME from the field. In order to achieve a nutrient balance that followed the redfield ratio **[38]**, the ratio of additional nutrients such as fertilizer and CO_2 to our proposed microalgae culture was empirically formulated as shown in **Table 2**. Based on the previous research, the removal efficiency (%) was up to 90% for total nitrogen and phosphorus content in anaerobic POME **[13, 24-26]**.

Furthermore, the energy footprint was calculated as CED [MJ] with respect to the life phases (cultivation, harvest, extraction and conversion), formulated as:

$$CED = \sum CED_{stage} = CED_{cultivation} + CED_{harvest} + CED_{extraction} + CED_{conversion} \quad (1)$$

Meanwhile, to determine energy demand for each stage, *CED* was calculated as the sum of all primary energy consumption due to the production of all process energy and materials directly used in each sub-stage, as follows:

$$CED_{stage} = \sum_i \sum_j EC_{i,j} \cdot PE_j + \sum_i \sum_n M_{i,n} \cdot PE_n \quad (2)$$

where $EC_{i,j}$ is the process j energy consumption during sub-stage i [MJ]; PE_j is the life cycle primary fossil energy use for process j energy production [MJ MJ^{-1}]; $M_{i,n}$ is the material n consumption during sub-stage i [kg]; PE_n is the life cycle primary energy use for material n production [MJ kg^{-1}].

Moreover, the ratio between total possible energy productions to total energy need can be presented by the following formula:

$$Energy\ Profit\ Ratio\ (EPR) = \sum E_{prod}/CED \quad (3)$$

where, $\sum E_{prod}$ is the total energy that can be produced including co-products in each stage [MJ].

Overall GHG emissions of a bioenergy supply chain were calculated based on the following formula, comprised of emissions accumulation:

$$GHG = \sum e_{stage} = e_{cultivation} + e_{harvest} + e_{extraction} + e_{conversion} \quad (4)$$

The unit for all variables is [g-CO_2eq MJ^{-1}-product].

Meanwhile, the total volume of water used to produce specific crops or trees (*WF*) is the sum of the green, blue, and grey components:

$$WF = \sum WF_{green} + \sum WF_{blue} + \sum WF_{grey} \quad (5)$$

The water footprint (*WF*) has the unit of m^3-water kg^{-1}-product.

3. Results and Discussion

3.1 Material and energy balance

The comprehensive life cycle assessment for integrated palm oil and microalgae production system are presented in **Table 3** and **Table 4**. **Table 3** summarized the material and energy balances for the palm oil-based biodiesel production cycle. In the nursery phase, material inputs for palm oil production include fertilizers, plant protection chemicals and water. The negative value in the LCA specifies the energy and GHG emission that can be avoided during the processes. Furthermore, it also indicates the avoided processed or freshwater water utilization as categorized in blue water footprint. Irrigated water is used mainly during the nursery stage by approximately 3.5 L d^{-1} for each palm tree. In the field, each hectare is normally planted with 350 palm trees. At the nursery stage, palm oil trees consumed a high amount of pesticides, herbicides and fertilizers, applied up to three times per year. The nursery phase takes approximately 48 months before a palm tree is ready to be planted in the palm grove. Most of the GHG emission emerge from utilization of agrochemicals in the form of fertilizer and plant protection.

Furthermore, for matures palm trees, soil conditioning was applied by controlling the soil acidity. Lime fertilizer and organic compost were commonly used in the field. Based on field measurements, the palm oil plantation required approximately 1,271.02 kg-fertilizer $ha^{-1}year^{-1}$ from various sources. Urea consumption was approximately 127.30 kg $ha^{-1}year^{-1}$ or 10% of the total annual required chemical-based fertilizers. However, urea has the highest embedded energy (62 MJ kg^{-1}) compared to other N fertilizer sources **[39]**. In addition, the plantation also requires diesel fuel as imported energy to run machinery and this led to a lower EPR for the biodiesel production. The FFB yield for each hectare was reported around 19.43 tons $year^{-1}$. Meanwhile, POME was produced approximately 42 m^3 h^{-1} or 800 m^3 d^{-1} from the existing mill. The palm oil mill was equipped with open ponding system to treat POME due to their low costs and operational simplicity.

In general, at the existing mill, 60 tons FFB h^{-1} can be extracted as CPO and PKO of 20.00% and 4.60% each, respectively. If a co-located biodiesel plant is installed and a conversion efficiency of 92% is used (based on our field survey and experiment), it is estimated that this integrated plant could produce 26,248 tons of palm oil-based biodiesel annually.

Further, the material and energy balance of microalgae-based biodiesel can be seen in **Table 4**. The results indicate that the largest impacts across all stages come from fertilizer and electricity use, emphasizing the need for technology improvements. Referred to our field measurements, the monthly average of CNP ratio in POME at a selected mill was 36:6:1. The ideal nutrient mix based on our previous experiment was approximately 56:8:1 for C:N:P, respectively. Thus, additional nutrients such as synthetic fertilizers and flue gases (CO_2 & NO_x) were required to reach the optimum nutrient balance. Sufficient nutrient supply for growing microalgae is an important factor to produce large quantities of biomass. Nitrate (NO_3^-), urea ($CO(NH_2)_2$), and ammonia (NH_4^+) appeared to be the most commonly used as the alternative for nitrogen sources **[39-40]**.

POME after the anaerobic digester still contains certain level of ammonia which has high nitrogen mass fraction, and suitable for microalgae growth, might lower additional synthetic fertilizer **[13, 25, 41, 42]**. Our study indicated that production of 1 kg of biodiesel from microalgae (in freshwater) required at least 0.83 kg of urea. This number could be brought down to 0.20 kg of urea (75.90% lower) per kg of microalgae-based biodiesel due to nitrogen compounds in POME from the anaerobic digester. POME utilization for microalgae culture brought lower the embedded energy input as a result of avoided fertilizer and reduce the GHG emission. The resource efficiencies can be achieved through the effluent treatment and biomass production. Further, our analysis showed that ammonia utilization potentially increased the EPR during the cultivation stage.

Adjacent to nutrients, paddlewheels were also consumed a large amount of energy during the cultivation stage. The total energy consumption for paddlewheel open pond system was estimated at 1.74 W m^{-3} or 62.64 kWh ha^{-1} d^{-1}, to generate a 30 cm s^{-1} mixing **[43]**.

During harvesting process, addition of flocculants improves the rate of sedimentation. Alum (aluminum sulfate) was assumed to be used in the harvesting process. This effective inorganic-flocculant has an embodied energy of approximately 10.4 MJ kg^{-1} **[44]**. Approximately 500 g-flocculant m^{-3} of biomass slurry were required **[44-47].** The flocculation-assisted sedimentation was assumed possible to increase the biomass concentration up to 3.00%dw with 90% of recovery rate **[47]**.

Moreover, to reduce the energy demand for dehydration process, waste heat (as much as 1.43 MJ kg^{-1}-biodiesel) from the biomass and biogas power plant potentially can be utilized. For 184.8 kg $ha^{-1}d^{-1}$ biomass production, the total required heat supply for dehydration process is approximately 1,110 MJ d^{-1}, to reduce water content below 10%. Approximately 10% or 129.55 GJ d^{-1} of total heat generated from biomass and biogas power plant practically can be used for dehydration process, which is more than enough as an alternative heat source.

Further, the biomass slurry sent to a belt filter press, to increase the concentration up to 30%dw. The lipid content from cell lysing and extraction process from the concentrated biomass was then processed by a transesterification method to produce biodiesel. Our experimental results of calorific value measurement indicate that the biodiesel energy content for palm oil and microalgae was approximately 39.60 MJ kg^{-1} and 36.76 MJ kg^{-1}, respectively. These results corresponded with the previous published reports **[48, 49]**.

The cell lysing and extraction processes leftover 70% of defatted biomass as protein and carbohydrate cake. Furthermore, 10 ha microalgae culture potentially can produce 520.33 tons of defatted biomass which can be utilized as an animal feed with high protein content **[50-53]**. Utilization of expeller as a fodder added other benefits to the total product life-cycle. Based on our calculations, avoided landfilling of the de-fatted biomass contributes to energy saving approximately 7.59 – 9.01

MJ kg^{-1} of produced animal feed, thus increase the integrated system efficiency as much as 0.096 MJ kg^{-1} palm oil based biodiesel.

Fig. 5 visualizes the total water footprint for the palm oil and microalgae material and energy balances as given in **Tables 3** and **4**. From the calculation results, both microalgae and palm oil had a lower water footprint compared to other biofuel crops. For microalgae cultivation, freshwater from technical irrigation could be added regularly to compensate water loss due to evaporation and maintain salinity. The supernatant drained from dehydration process could also be returned to the cultivation ponds in order to reduce external water requirement and optimize nutrient recycled. Meanwhile, throughout the cultivation stage, the palm oil plantation utilized technical irrigation for a proportional watering system, especially during the nursery period. Microalgae cultivation utilized effluent from the palm oil mill, which is a grey water category, and contributed to lowering the environmental load.

Microalgae culture is an energy intensive **[54]**, thus wastewater based cultivation is a good option to lower the synthetic fertilizer need **[55]**. In addition, 161.59 tons of CO_2 $year^{-1}$ from biomass and biogas power plants potentially can be supplied to each hectare of microalgae culture for nutrient balance. As a result of simulation, the estimated of real nutrients substitution and its contribution to energy and CO_2eq footprint are summarized in **Table 5**. The resource efficient was made by reduction of synthetic fertilizer use while also lower the energy and CO_2eq footprint. It is clear that following the future demands of biodiesel, a complement of microalgae biodiesel would significantly reduce fertilizer requirements.

Palm oil based biodiesel contributed to 62.37 g CO_2eq MJ^{-1} of GHG emission or 25.57% lower than current diesel fossil fuel reference (83.8 g CO_2eq MJ^{-1}) as stated in EU renewable energy directive 2015 **[56]**. Meanwhile, 49.78 g CO_2eq MJ^{-1} for microalgae based biodiesel cultivated in POME or 40.59% lower than diesel fossil fuel reference. Microalgae cultivation for effluent treatment and co-products utilization as animal feed would help to lower the total CO_2eq footprint. Another possible GHG mitigation option is composting, since organic fertilizer potentially able to substitute nitrogenous synthetic fertilizers and reducing their use.

3.2 Integrated bioenergy system

Integrating microalgae system at the palm oil mill to produce bioenergy offers many potential synergies. Several scenarios were considered to optimize energy utilization inside the plantation by various combinations: palm oil- and microalgae-based biodiesel, biomass power plant (shell and fiber), and biogas power plant. The average biodiesel density was around 0.88 kg L^{-1}, and the total biodiesel that could be produced at the optimum plant capacity was approximately 26,248 tons $year^{-1}$ and 223 tons $year^{-1}$ from CPO and microalgae, respectively. Meanwhile, the combined of total biodiesel energy is around 1,047 TJ $year^{-1}$.

As shown in **Fig. 6** from 1 ton of FFB, after crude oil extraction, approximately 0.13 ton, 0.07 ton, and 0.23 ton of fiber, shell, and empty fruit bunch (EFB) can be produced, respectively. As the heating value of solid waste is approximately 20 MJ kg^{-1} then, at 30% energy conversion efficiency, about 50% of the total solid waste can be used as fuel stock for 4.5 MW of steam turbine at mill. At least 15,000 tons of shell and fiber per year at 45% moisture content are required as the fuel stock for a 1 MW biomass power plant with 90% uptime. Meanwhile, the remaining solid waste including EFB is used for organic fertilizer and landfill practices (53.49%).

However, the availability of POME and nutrients balance become the limiting factor for the growth of microalgae in POME. Our investigation showed that wastewater generated from POME was at least 3.5 m^3 POME/t CPO or 1.5 m^3 POME/t FFB of volume estimation **[13]**. The POME availability was based on the realistic analysis and minimum volume that potentially can be utilized for microalgae cultivation, since not all of the wastewater can be used as it contains large amount of sludge (a mixed solid waste) and drainage for internal use or irrigation. The proposed microalgae size was only 0.9% (10 ha) compared to the required size (1,170 ha) to reach similar annual biodiesel production capacity from palm oil (26,248 tons) planted in approximately 10,630 ha. Thus, the ratio of biomass productivity per ha between microalgae and palm oil was differed approximately 9 times.

Fig. 7 expresses the energy aggregate for several integrated system scenarios. The microalgae-based biodiesel had small contribution to the total energy output since the cultivation size was only designed for 10 ha, inside the palm oil plantation. Scenario (5) shows an energy balance with additional biodiesel production from 1,170 ha of microalgae culture. However, to reach up to 1,170 ha of cultivation pond was quite difficult in the current condition due to limited source of POME (20,000 m^3 $month^{-1}$). However, discharge water from harvesting stage could be recycled for nutrient recovery and maintain water supply. High content of organic compounds, such as acetic acid from aqueous products of extraction process and anaerobic digestion process can be used for additional nutrients **[57]**. Moreover, some challenges might be found during implementation in actual conditions, since maintaining optimal and stable cultivation conditions at the commercial scale is relatively difficult.

Fig. 8 indicates the EPR for each potential bioenergy sources inside the palm oil plantation. The biogas power plant had the highest EPR since the ratio of energy output (produced) was very high compare to its energy input. Biogas as much as 16.8 m^3-Biogas/m^3-POME produced from the anaerobic POME treatment system was utilized to generate power and had a prospective energy production of 89.6 TJ $year^{-1}$, equal to 1.2 MW of power generation **[13]**. The EPR was around 5.40 for biomass power plant by utilizing shells and fibers to generate steam. The total EPR might be higher if dry EFB is used as the additional boiler fuel stock. However, practically most of solid wastes and effluent are utilized for organic fertilizers in the plantation to suppress the use of chemical fertilizers. Overall, the EPR for the proposed integrated system was 5.20, which indicate that the total bio-energy that could be produced was more than 5 times higher than the total energy required. The energy generation process was assumed CO_2-neutral, and largely independent from fossil fuels. The specific CO_2eq emissions per ton of biomass were 1.01 tons. Meanwhile, the POME had potential emission rate of 190 to 600 kg-CO_2eq ton^{-1}-FFB **[58, 59]**. **Table 6** summarizes the results of CO_2eq emissions calculation for each potential bioenergy source inside the plantation.

Improved energy balances from an integrated bioenergy system provided strong environmental benefits. Since most of the existing agricultural machinery and trucks inside the plantation run on diesel, substituting and blending the diesel fuel with domestic biodiesel production is feasible and potentially reduce the imported energy. Furthermore, compare with GHG emission from diesel fuel of 83.8 gCO_2eq MJ^{-1} **[54, 58-60]**, at least 39,295 tons CO_2eq year^{-1}could be avoided (36.90% GHG emission reduction) by diesel fuel substitution from palm oil and microalgae. In addition, biomass and biogas power generation also contribute to emission reduction as much as 20,766 tons CO_2eq year^{-1} or 60.73% lower than current average emission factor from the national power grid in Indonesia.

4. Conclusions

The results in this study showed that the integrated bioenergy system offers several positive synergies and can concluded as:

1. The EPR aggregate of the integrated bioenergy system was 5.20. The proposed model contributed to total biodiesel production potential of 26,471 tons year^{-1} (which include 223 tons from 10 ha microalgae cultivation), and 45 GWh year^{-1} of total power generated from biomass and biogas power plant.
2. A relatively low water footprint could be gained, approximately 3.18 m^3-water kg^{-1}-biodiesel and 2.85 m^3-water kg^{-1}-biodiesel for palm oil and microalgae, respectively.
3. POME and flue gases from biomass and biogas power plant as an alternative medium and nutrient sources contribute to net-reduction of GHG emission for 158.8 tons ha^{-1} of microalgae culture, annually. Co-location of microalgae facilities in the palm oil plantation provides benefits in the future.

In addition, the related experiments would be reported in our further research focusing the evaluation of the system dynamic, which is also necessary to be demonstrated for understanding and provide a comprehensive environmental impact assessment.

5. Acknowledgements

This work was supported by the Indonesia scholarship program for research and innovation in science and technologies (RISET-PRO) World Bank Loan No. 8245-ID and a grant of Next-generation renewable energy development program for Fukushima reconstruction and revitalization, Fukushima Prefecture, Japan for 2013-2015.

6. References

[1] Mekonnen MM, Hoekstra AY. Water footprint benchmarks for crop production: A first global assessment. Ecological Indicators 2014;46:214-223. https://doi.org/10.1016/j.ecolind.2014.06.013

[2] Searchinger TD. Biofuels and the need for additional carbon. Environ Res Lett 2010;5:10:024007(10pp). https://doi.org/10.1088/1748-9326/5/2/024007

[3] YARA. YARA fertilizer industry handbook. 2017.
See also: http://yara.com/doc/245619_Fertilizer_Industry_Handbook_2017.pdf; 2017.

[4] Ecoinvent 3.1 Database. Swiss centre for life cycle inventories. Dübendorf: in Simapro 8.1; 2016.

[5] APPI (Indonesia Fertilizer Producers Association). Fertilizer production, year 2007- 2017. 2017.
See also: http://appi.or.id/download.php?kat=statistic&fileid=177 [accessed 01.04.2017]

[6] Gerbens-Leenes W, Hoekstra AY. The water footprint of biofuel-based transport. Energy & Environmental Science 2011;4(8):2658-2668. https://doi.org/10.1039/C1EE01187A

[7] Hoekstra AY. A critique on the water-scarcity weighted water footprint in LCA. Ecological Indicators 2016;66:564-573. https://doi.org/10.1016/j.ecolind.2016.02.026

[8] Mekonnen MM, Hoekstra AY. The green, blue and grey water footprint of crops and derived crop products. Hydrol Earth Syst Sci 2011;15:1577-1600. https://doi.org/10.5194/hess-15-1577-2011

[9] Yang J, et al. Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance. Bioresource Technology 2011;102(1):159-165.
https://doi.org/10.1016/j.biortech.2010.07.017

[10] Mathew DC. Improving microalgae biofuel production: an engineering management approach. Ph.D dissertation edition. Cranfield university 2014. http://dspace.lib.cranfield.ac.uk/handle/1826/9304

[11] ANL, NREL, PNNL. Renewable diesel from algal lipids: An integrated baseline for cost, emissions, and resource potential from a harmonized model 2012.
See also: http://www.nrel.gov/docs/fy12osti/55431.pdf [accessed 01.01.2017]

[12] MEMR. Mandatory of biodiesel utilization no 12 March 18th. The ministry of energy and mineral resources regulation of Indonesia 2015.
See also: http://jdih.esdm.go.id/peraturan/Permen%20ESDM%2012%20Thn%202015.pdf; 2017

[13] Sasongko NA, Noguchi R, Ahamed T, Takaigawa T. Introduction of integrated energy plantation model for microalgae-using Palm Oil Mill Effluent (POME). Journal of the Japan Institute of Energy

2015;94(6):561-570. http://doi.org/10.3775/jie.94.561

[14] Lam MK, Lee KT. Potential of using organic fertilizer to cultivate *Chlorella vulgaris* for biodiesel production. Applied Energy 2012;94:303-308. https://doi.org/10.1016/j.apenergy.2012.01.075

[15] Siregar K, et al. A comparison of life cycle assessment on oil palm (*Elaeis guineensis Jacq.*) and physic nut (*Jatropha curcas Linn.*) as feedstock for biodiesel production in Indonesia. Energy Procedia 2015;65:170-179. https://doi.org/10.1016/j.egypro.2015.01.054

[16] Silalertruksa T, Gheewala SH. Environmental sustainability assessment of palm biodiesel production in Thailand. Energy 2012;43(1):306-314. https://doi.org/10.1016/j.energy.2012.04.025

[17] Sasongko NA, Thorns C, Sankoff I, Chew ST, Bista S. Transitioning to sustainable use of biofuel in Australia. Renew. Energy Environ. Sustain. 2017;2:25. https://doi.org/10.1051/rees/2017034

[18] Clarens AF, Resurreccion EP, White MA, Colosi LM. Environmental life cycle comparison of algae to other bioenergy feedstocks. Environ Sci Technol 2010;44(5):1813–1819. https://doi.org/10.1021/es902838n

[19] Slade R, Bauen A. Microalgae cultivation for biofuels: cost, energy balance, environmental impacts and future prospects. Biomass and Bioenergy 2013;53:29–38. https://doi.org/10.1016/j.biombioe.2012.12.019

[20] Cooney MJ, Young G, Pate R. Bio-oil from photosynthetic microalgae: case study. Bioresource Technology 2011;102(1):166-177. https://doi.org/10.1016/j.biortech.2010.06.134

[21] Passell H, et al. Algae biodiesel life cycle assessment using current commercial data. Journal of Environmental Management 2013;129:103-111. https://doi.org/10.1016/j.jenvman.2013.06.055

[22] Gibbs HK, et al. Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. Environ Res Lett 2008;3:10pp. https://doi.org/10.1088/1748-9326/3/3/034001

[23] Wicke B, Dornburg V, Junginger M, Faaij, A. Different palm oil production systems for energy purposes and their greenhouse gas implications. Biomass and Bioenergy 2008;32:1322-1337. https://doi.org/10.1016/j.biombioe.2008.04.001

[24] Hadiyanto, Azimatun Nur MM. Lipid extraction of microalga *Chlorella sp.* cultivated in Palm Oil Mill Effluent (POME) medium. World Applied Sciences Journal 2014;31(5):959-967. https://doi.org/10.5829/idosi.wasj.2014.31.05.2006

[25] Ichsan, Hadiyanto H, Hendroko R. Integrated biogas-microalgae from wastewaters as the potential biorefinery sources in Indonesia. Energy Procedia 2014;47:143-148. https://doi.org/10.1016/j.egypro.2014.01.207

[26] Cheirsilp B, Tippayut J, Romprom P, Prasertsan P. Phytoremediation of secondary effluent from palm oil mill by using oleaginous microalgae for integrated lipid production and pollutant removal. Waste Biomass Valor 2016;1-9. https://doi.org/10.1007/s12649-016-9751-6

[27] Lardon L, et al. Life cycle assessment of biodiesel production from microalgae. Environmental

Science & Technology 2009;43(17):6475-6481. https://doi.org/10.1021/es900705j

[28] Beal CM, et al. Energy return on investment for algal biofuel production coupled with wastewater treatment. Water Environment Research 2012;84(9):692–710. https://doi.org/10.2175/106143012X13378023685718

[29] Batan L, Quinn J, Willson B, Bradley T. Net energy and greenhouse gas emission evaluation of biodiesel derived from microalgae. Environmental Science & Technology 2010;44(20):7975–7980. https://doi.org/10.1021/es102052y

[30] ISO 14044. Environmental management - life cycle assessment - requirements and guidelines 2006. See also: https://www.iso.org/standard/38498.html

[31] IPCC. Climate change 2013, the physical science basis. Intergovernmental Panel on Climate Change 2013. See also: http://www.ipcc.ch/report/ar5/wg1/ [accessed 01.08.2016]

[32] Simorangkir D. Fire use: is it really the cheaper land preparation method for large-scale plantations? Mitig Adapt Strat Glob Change 2007;12(1):147–164. https://doi.org/10.1007/s11027-006-9049-2

[33] Johari A, et al. The challenges and prospects of palm oil based biodiesel in Malaysia. Energy 2015;81:255-261. http://dx.doi.org/10.1016/j.energy.2014.12.037

[34] Polprasert C, Patthanaissaranukool W, Englande AJ. A choice between RBD (refined, bleached, and deodorized) palm olein and palm methyl ester productions from carbon movement categorization. Energy 2015;88:610-620. https://doi.org/10.1016/j.energy.2015.05.108

[35] BPPT. Indonesia energy outlook 2017. The agency for assessment and application of technology 2017. See also: http://bppt.go.id/outlook-energi/bppt-outlook-energi-indonesia-2017/download

[36] IGES. List of grid emission factor. Excell file. Institute for global environmental studies 2017. See also: https://pub.iges.or.jp/pub/list-grid-emission-factor [accessed 01.03.2017].

[37] Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM. The water footprint assessment manual: setting the global standard. Earthscan 2011. See also: http://waterfootprint.org/media/downloads/TheWaterFootprintAssessmentManual_2.pdf [downloaded 01.05.2016]

[38] Hillebrand H, Sommer U. The nutrient stoichiometry of benthic microalgal growth: Redfield proportions are optimal. Limnol Oceanogr 1999;44(2):440-446. https://doi.org/10.4319/lo.1999.44.2.0440

[39] Harsono SS, et al. Energy balances and greenhouse gas emissions of palm oil biodiesel in Indonesia. GCB Bioenergy 2012;4:213–228. https://doi.org/10.1111/j.1757-1707.2011.01118.x

[40] Lam MK, Lee KT. Potential of using organic fertilizer to cultivate *Chlorella vulgaris* for biodiesel production. Applied Energy 2012;94:303-308. https://doi.org/10.1016/j.apenergy.2012.01.075

[41] Sathish A. Biodiesel production from mixed culture algae via a wet lipid extraction procedure. All graduate theses and dissertations. Paper 1372. Utah State University 2012. See also: http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=2361&context=etd

[downloaded 01.03.2016]
[42] Phang SM, Ong KC. Algal biomass production in digested palm oil mill effluent. Biological Wastes 1988;25:177-191. https://doi.org/10.1016/0269-7483(88)90078-X
[43] Rogers JN, et al. A critical analysis of paddlewheel-driven raceway ponds for algal biofuel production at commercial scales. Algal Research 2014;4:76-88. https://doi.org/10.1016/j.algal.2013.11.007
[44] Vandamme D. Flocculation based harvesting processes for microalgae biomass production. Doctor in Bioscience Engineering Disertation. KU Leuven 2013.
See also: www.vliz.be/imisdocs/publications/254002.pdf [downloaded 01.05.2016]
[45] Gutiérrez R, et al. Harvesting microalgae from wastewater treatment systems with natural flocculants: effect on biomass settling and biogas production. Algal Research 2015;9:204-211. http://dx.doi.org/10.1016/j.algal.2015.03.010
[46] Granados MR, et al. Evaluation of flocculants for the recovery of freshwater microalgae. Bioresource Technology 2012;118:102–110. http://dx.doi.org/10.1016/j.biortech.2012.05.018
[47] Milledge JJ, Heaven S. A review of the harvesting of micro-algae for biofuel production. Rev Environ Sci Biotechnol 2013;12(2):165–178. https://doi.org/10.1007/s11157-012-9301-z
[48] Frank ED, et al. Life cycle analysis of algal lipid fuels with the GREET model. Argonne National Laboratory 2011. See also: https://greet.es.anl.gov/files/algal-lipid-fuels [accessed 01.12.2016]
[49] Tesfa B, Gu F, Mishra R, Ball AD. LHV predication models and LHV effect on the performance of CI engine running with biodiesel blends. Energy Conversion and Management 2013;71:217-226. https://doi.org/10.1016/j.enconman.2013.04.005
[50] Lodge-Ivey SL, Tracey LN, Salazar A. The utility of lipid extracted algae as a protein source in forage or starch-based ruminant diets. J Anim Sci 2014;92(4):1331-1342. https://doi.org/10.2527/jas2013-7027
[51] Yaakob Z, et al. An overview: biomolecules from microalgae for animal feed and aquaculture. Journal of Biological Research-Thessaloniki 2014;21:6. https://doi.org/10.1186/2241-5793-21-6
[52] Lum KK, Kim J, Lei XG. Dual potential of microalgae as a sustainable biofuel feedstock and animal feed. J Anim Sci Biotechnol 2013;4(1):53. https://doi.org/10.1186/2049-1891-4-53
[53] Dib M. *Chlorela sp.*: lipid extracted algae utilization of algae biodiesel co-products as an alternative protein feed in animal production. Ph.D Diss. Ed. Colorado State University 2012.
See also:
https://dspace.library.colostate.edu/bitstream/handle/10217/71555/Dib_colostate_0053A_11560.pdf?sequence=1 [downloaded 01.06.2015]
[54] Frank ED, et al. Methane and nitrous oxide emissions affect the life-cycle analysis of algal biofuels. Environ Res Lett 2012;7:10. https://doi.org/10.1088/1748-9326/7/1/014030
[55] Menger-Krug E, Niederste-Hollenberg J, Hillenbrand T, Hiessl H. Integration of microalgae systems

at municipal wastewater treatment plants: implications for energy and emission balances. Environmental Science & Technology 2012;46(21):11505-11514. dx.doi.org/10.1021/es301967y

[56] de Jong S, et al. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. Biotechnology for Biofuels 2017;10:64. https://doi.org/10.1186/s13068-017-0739-7

[57] Biller P, et al. Nutrient recycling of aqueous phase for microalgae cultivation from the hydrothermal liquefaction process. Algal Research 2012;1:70-76. https://doi.org/10.1016/j.algal.2012.02.002

[58] USAID. Handbook POME-to-biogas project development in Indonesia. Second edition ed. Jakarta: Winrock International 2015.
See also: https://www.winrock.org/wp-content/uploads/2016/05/CIRCLE-Handbook-2nd-Edition-EN-25-Aug-2015-MASTER-rev02-final-new02-edited.pdf [downloaded 01.06.2016]

[59] RSPO. Greenhouse gas emissions from palm oil production. Literature review and proposals from the RSPO working group on greenhouse gases. Final report. ed. Brinkmann Consultancy 2009.
See also: http://www.rspo.org/files/project/GreenHouse.Gas.Working.Group/Report-GHG-October2009.pdf [downloaded 01.05.2015]

[60] Koh SL, Lim YS, Morris S. Cost effective options for greenhouse gas (GHG) emission reduction in the power sector for developing economies — a case study in Sabah, Malaysia. Energies 2011;4:780-803. https://doi.org/10.3390/en4050780