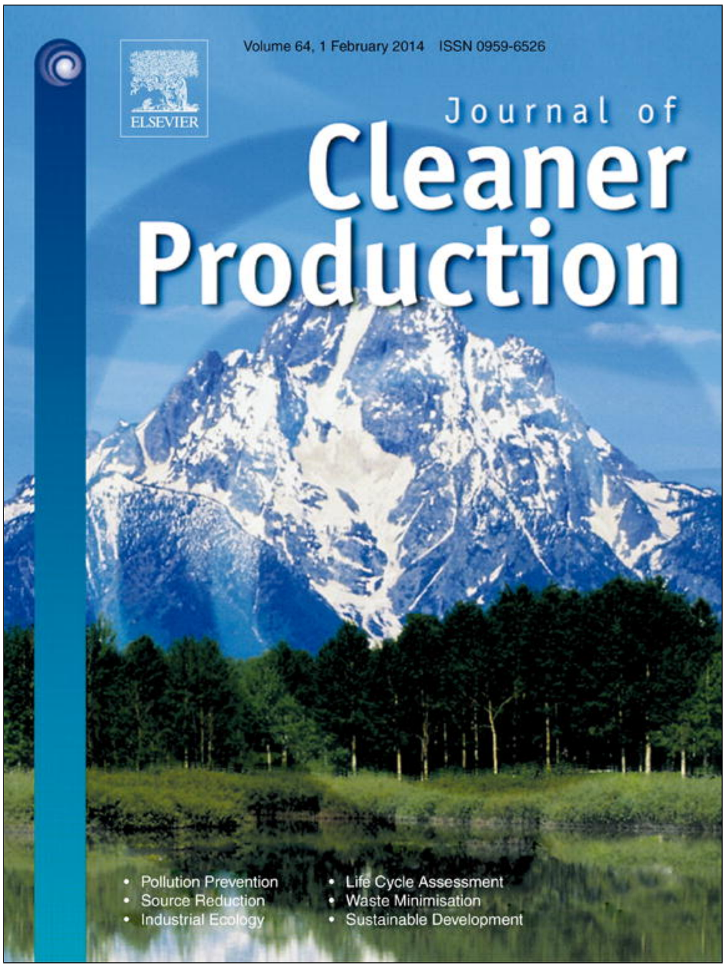
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Anaerobic treatment of palm oil mill effluents: potential contribution to net energy yield and reduction of greenhouse gas emissions from biodiesel production

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ABSTRACT

The effluents from palm oil mills for biodiesel production are generally treated in open ponds, causing large amounts of greenhouse gas (GHG) emissions. This study assesses the use of palm oil mill effluents (POME) as feedstock to produce biogas via anaerobic digestion. Biogas from POME can be converted into electricity and heat to eventually reduce the greenhouse gas (GHG) emissions of biodiesel production from palm oil. This study is using two system boundaries, firstly, system a “gate-to-gate” concerning the POME treatments, and secondly a “cradle-to-gate/total combustion” when we assess the impact of varying POME treatments within the biodiesel chain.

The research draws on field and experimental data from palm oil and biogas production in Sumatra, Indonesia. The findings show that the energy output from the conversion of POME to methane via anaerobic digestion and the subsequent combustion of the methane in a combined heat-power plant exceeds the energy consumption of the palm oil milling process. Treating POME in an anaerobic digester and using the biogas to generate electricity and heat has the potential to significantly reduce the GHG emissions of biodiesel production from palm oil. In the studied case, the energy output from the conversion of POME to electricity and heat is 0.44 MJ kg^{-1} biodiesel and the net energy yield is 0.42 MJ kg^{-1} biodiesel. The ratio of energy output to energy input of the conversion process is about 23.1. The potential reduction of GHG emissions is 658 g $CO_{2\text{-eq}}$ kg^{-1} biodiesel or 15.96 g $CO_{2\text{-eq}}$ MJ^{-1}. This is equivalent to about 33% of the total GHG emissions of biodiesel production from palm oil. Against this background we recommend to further develop and implement the treatment of POME in anaerobic digestion combined with the purposeful use of the methane, electricity and heat produced from the POME. This can make a significant contribution toward meeting international targets of emissions reduction for biodiesel production.

1. Introduction

1.1. Background

Indonesia produced nearly 25 million metric ton of palm in 2011/2012 (USDA, 2012). It is estimated that about 28 m^3 of biogas is generated for every m^3 of palm oil waste of the waste treatment plant of palm oil mills. In the palm oil mills, solid wastes are burned directly in the boiler to generated steam. There are many solid wasted included the fiber, shell and empty fruit bunches (EFB). Palm oil cultivation has become one of the dominant agricultural activities in Indonesia since the late 1990s. Between 1998 and 2007

Abbreviations: CH_4, methane; CHP, combined heat and power; $CO_{2\text{-eq}}$, carbon dioxide equivalents; COD, Chemical Oxygen Demand; CPO, crude palm oil; d, day; EFB, empty fruit bunches; FFB, fresh fruit bunches; g, gram; GHG, greenhouse gases; GWP, Global Warming Potential; ha, hectare; hr, hour; IOPRI, Indonesian Oil Palm Research Institute; LUC, land use change; POME, palm oil mill effluent; yr, year.

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the total area cultivated with palm oil increased from 3.9 million ha to more than 7.9 million ha (Rianto, 2009).

Nevertheless, Laurance et al. (2010) and Yule (2010) stated that sustainability of palm oil production as always been questioned by some countries and the non-governmental organization (NGOs). They claimed that further expansion of palm oil plantation cause more negative impact for environmental such deforestation and increasing greenhouse gas (GHG) emissions due to over utilization of peat land for palm oil plantation.

The criticism not only in the palm oil plantation expansion, but also include in the palm oil mills. Poh and Chong (2009) argued that the most significant pollutant from the palm oil mills is palm oil mill effluent (POME). The increasing production of CPO is accompanied by an increasing output of effluent from palm oil mills. Yacob et al. (2005) and Singh et al. (2010) reported that palm oil mills treat in average 60% of the wastewater in open ponds before it is disposed to the natural waters, while untreated wastewater is mainly used as liquid fraction in the composting process of empty fruit bunches.

However, there are large quantities of water based wastes that are not able to burn by themselves. These wastes have to be processed or digested in the waste treatment plant on order to comply with Department of Environment the Republic of Indonesia regulation before they can be allowed to be discharged into the water course. During the fermentation process, biogas is the unavoidable but valuable gaseous product of such a process.

North Sumatra province of Indonesia has a significant number of large agricultural operations. These agricultural operations produce a considerable amount of organic waste in the form of palm oil mill effluent (POME). Handling such large amounts of organic wastes, especially POME, in a environmentally friendly manner a highly challenging.

Given this huge amount of palm oil production, therefore the quantity of waste produced is expected to be large. These wastes, if not disposed properly, will have great negative impacts on the surrounding environment, i.e.: water pollution and greenhouse gas emissions.

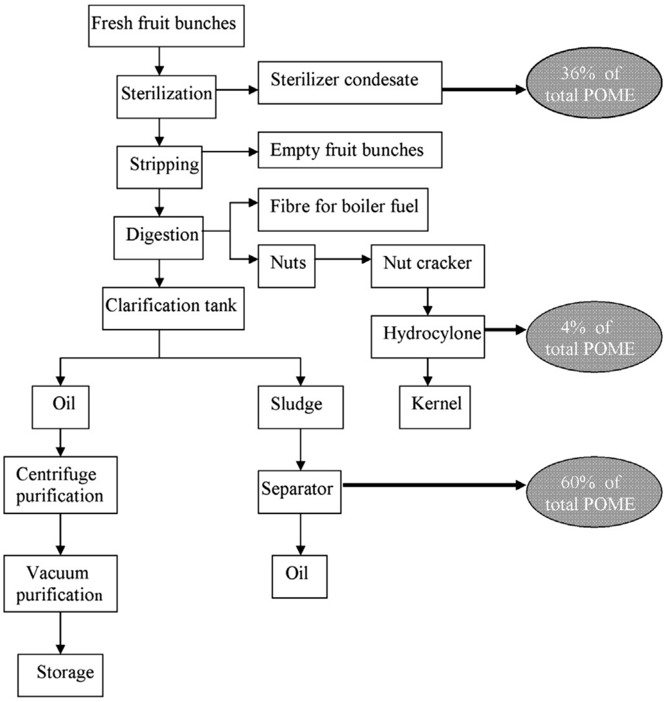

Fig. 1. Simplified process flow diagram of the production of crude palm oil including palm oil mill effluents (POME) (Lam and Lee, 2010).

Compared to gas emissions and solid wasted production, wastewater management in crude palm oil mill has long been a topic of research and discussion.

Several researchers highlight that storing POME without adequate treatment in open ponds causes environmental degradation and high emissions of GHG (Yacob et al., 2005; Basri et al., 2010). The environmental degradation including much more water resources is polluted and makes irrigated areas.

Hence, immediate remedies should be taken to overcome this problem and further strengthen for utilization of POME as energy resources for biodiesel production as content of this study and more environmental friendly solutions for treating POME are desired.

1.2. Nature of POME and treatment process

1.2.1. Nature of POME

POME is the liquid effluent discharged from the palm oil mills as a thick brownish liquid at a temperature between 80 and 90 °C with a pH typically between 4 and 5 (Singh et al., 2010). It is a combination of wastewaters generated and discharged from sterilizer condensate (36% of total POME), clarification wastewater (60% of total POME) and hydrocyclone wastewater (nearly 4% of total POME) (Wu et al., 2009).

Fig. 1 shows flow diagram where the POME is produced from palm oil mill.

Sources of POME in the palm oil mill processing as shown in Fig. 1 are follow.

a. Sterilization of Fruit Fresh Bunch (FFB)

At the process of sterilization, pressured steam (3×10^5 Pa) at high temperature 140 °C is used to infuse moisture into the nuts which can cause it to expand (Wu et al., 2009). Beside that, sterilization has purpose to eliminated the oil-splitting enzymes and slow down the formation of free fatty acids in the oil. The last, sterilization is applied to ensure that air is expelled from sterilizer in order to avoid oxidation by air (Poku, 2002). The waste that is expelled from sterilizer is one of the major sources of POME.

b. Stripping, digestion and pressing the fruits

The stripping is to separate the sterilize fruits from the bunch stalks by using rotary drum thresher. The detached fruits are passed through a bar screen in the stripper, collected by a bucket conveyor and the send in to digester. In the digester, the fruit is softened by steam-heated cylindrical vessel fitted with central rotating at high temperature, between 80 and 90 °C, then the fruits mesocarp will be loosened from the nuts and delivered to mechanical press machine to squeeze out the crude palm oil (Wu et al., 2009).

c. Clarification

The purpose of clarification is to separate the oil from its entrained impurities. The fluid flowing out from the press machine is a mixture of palm oil, water, cell debris, and other insoluble solids that content high viscosity. Then, the hot water is added into the clarifier to break the oil emulsion and acts as barrier to cause the insoluble solids to settle to the bottom of the clarifier while the lighter oil droplets flow through the watery mixture on the top. Consequently, the bottom phase from the clarifier is drained off as sludge of POME for further purification before being discharged.

d. Kernel oil recovery

Press cake form the press machine consists of a mixture of fiber and nuts. After the separation of fiber from the nuts by strong air current induced by a suction fan, the fiber is usually sent to boiler as fuel while the nuts are sent to a nut cracker and then send finally to the hydrocyclone. It is commonly used to separate the kernels from empty fruit shells after cracking the nuts. This process produces the last of source of POME (Wu et al., 2009).

According to Yacob et al. (2005), palm oil mills discharge about 2.5 m^3 POME t^{-1} CPO produced or 0.5 m^3 POME t^{-1} FFB (fresh fruit bunches) processed. Sumanthi et al. (2008) found that the average amount of POME produced in palm oil mills in Indonesia is 3.5 m^3 POME t^{-1} CPO or 0.7 m^3 POME t^{-1} FFB, and Basri et al. (2010) stated that approximately 1.5 m^3 POME t^{-1} FFB is typically produced in palm oil processing.

1.2.2. POME treatment processes

The increasing production of palm oil has raised the question of how to manage the increasing volume of POME efficiently and preserving the environment. Commonly, POME is treated in ponds under aerobic conditions. The treatment system using open ponds is simple and requires low investment and low energy input. Basri et al. (2010) compile some negative aspects of the ponding system such as high area demand (>5 ha for a palm oil mill with a throughput of 30 t FFB hr^{-1}), reduction of the effective volume of the ponds due to the accumulation of sludge in the bottom of the ponds, and high costs for the *de-sludging* of the ponds and handling of the sludge. The ponding system also results in long hydraulic retention times, low treatment efficiency, high sludge production and emissions of large amounts of GHG, including CH_4 and CO_2 (Yacob et al., 2005; Sumanthi et al., 2008). Hojjat and Salleh (2009) estimated that as much as 10 m^3 CH_4 t^{-1} FFB are emitted from the POME stored in ponds. In addition, all the nutrients including N, P, K, Mg, and Ca in the POME are released into adjacent bodies of water, polluting the environment and causing economic losses (Ahmad et al., 2004).

Alternative processes for the treatment of POME are mentioned in the literature, including composting (Rupani et al., 2010; Singh et al., 2010; Stichnothe and Schuchardt, 2010), covering the ponds with a flexible membrane or constructing covered tanks (Hansen et al., 2012) and anaerobic treatment in digestion plants (Yacob et al., 2005; Basri et al., 2010). All treatment options aim to reduce the discharges of wastewater, and to recycle POME and capture methane to reduce GHG emissions and substitute non-renewable fuels consumed in the palm oil and biodiesel production process.

Achten et al. (2010), Lam and Lee (2010), and Foo and Hameed (2010) showed that the treatment of POME in anaerobic digestion plants. They found that the energy content of the methane obtained from the treatment of POME in anaerobic digestion plants was sufficient to cover the energy consumption of the palm oil mills. Choo et al. (2011) conducted an LCA of palm oil derived biodiesel based on an extensive study of several palm oil plantations, palm oil mills and biodiesel plants in Malaysia. The authors concluded that the production of palm oil derived biodiesel emits 33.19 g $CO_{2\text{-}eq}$ MJ^{-1} biodiesel without capture of methane from the open ponds and 21.20 g $CO_{2\text{-}eq}$ MJ^{-1} biodiesel with capture of methane from the open ponds. Harsono et al. (2011:12) estimated GHG emissions from the production of biodiesel of 1566 g $CO_{2\text{-}eq}$ kg^{-1} biodiesel without capturing the methane from the open ponds. Stichnothe and Schuchardt (2010) use LCA methodology to compare the GHG emissions of four different POME treatment strategies, including 1) the storage and treatment of POME in open ponds, 2) direct application of EFB and POME to the palm oil trees, 3) mixing POME with chopped EFB for composting and application of the compost to the trees, and 4) anaerobic digestion of POME. They indicated that the Global Warming Potential (GWP) of palm oil mill waste treatment can be reduced from 245 kg $CO_{2\text{-}eq}$ t^{-1} FFB until up to 5–7.4 kg $CO_{2\text{-}eq}$ t^{-1} FFB due to reduced methane emissions and nutrient recycling.

1.3. Study objectives

The overall objective of this study is to assess the potential contribution of the anaerobic treatment of POME in digestion plants to reduce fossil fuel consumption and lower GHG emissions in biodiesel production. The specific objectives are to compare the net energy yield and the GHG emissions of the aerobic treatment of POME in open ponds and the anaerobic treatment of POME in an anaerobic digestion plant.

2. Methodology

2.1. System boundaries and functional unit

The study compares the net energy yields and GHG emissions from the treatment of POME in open ponds with the treatment of POME in an anaerobic digester, including the production of heat and electricity from biogas. The process of POME treatment in an anaerobic digester and subsequent conversion of biogas is shown in Fig. 2 below, including the cooling in open ponds, the anaerobic digestion, and the generation of electricity and heat from biogas.

The Fig. 2 displays the system boundaries set for the assessment. The study focuses on the inputs and outputs of the anaerobic digestion of POME. For the analysis, we assume that 50% of the POME is treated in the anaerobic digester, while the remaining 50% of the POME continues to be treated in open ponds. The emissions outside the system boundaries are not considered in the assessment of the single POME treatment strategies in this study. For the assessment of the emissions from biodiesel production including the POME treatment we used the results published by Harsono et al. (2011) on the emissions from oil palm cultivation and biodiesel production from palm oil.

The functional unit in this assessment is 1 kg of biodiesel produced. Values are also given per hectare and year.

This study is using two system boundaries, firstly, system a “gate-to-gate” concerning the POME treatments, and secondly a “cradle-to-gate/total combustion” when we assess the impact of varying POME treatments within the biodiesel chain.

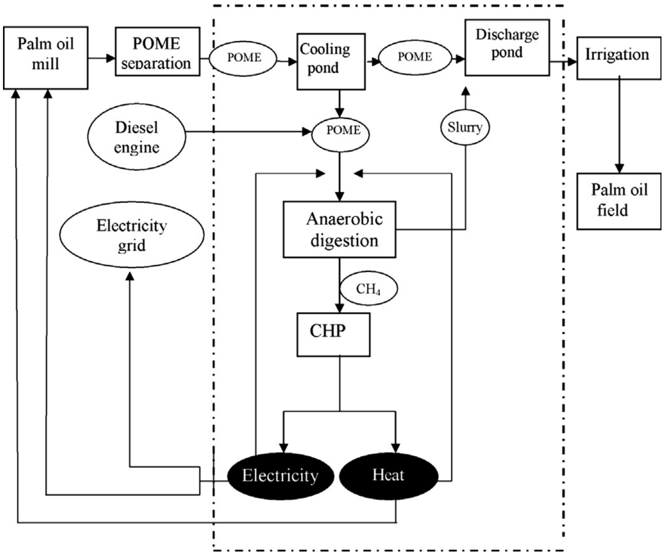

Fig. 2. System boundary (denoted by the dash line) of POME treatment with aerobic digestion in open ponds and anaerobic POME treatment in a digestion plant including the combustion of methane to heat and electricity.

Table 1
Operational data of the palm oil mill PT. Asam Jawa, North Sumatra, Indonesia.

Parameter	Unit	Value	Source
Mill operation hours	$hr\ yr^{-1}$	6240	Field data
Yearly mill operation time	$d\ yr^{-1}$	312	Field data
Area of the plantation	ha	13,000	Field data
FFB processed	$t\ yr^{-1}$	384,480	Field data
POME produced	m^3 POME yr^{-1}	234,936	Field data
POME yield	m^3 POME t^{-1} FFB	0.610	Field data
Average depth of ponds	m	5	Field data
Electricity consumption	$GJ\ yr^{-1}$	6.543	Field data
Diesel fuel consumption	$GJ\ yr^{-1}$	4.559	Field data

Remark.
$d\ yr^{-1}$: day per year.
m^3 POME yr^{-1}: meter cubic of POME per year.
m^3 POME t^{-1} FFB: meter cubic POME per ton Fruit Fresh Bunch.
m: Meter.
$GJ\ yr^{-1}$: Giga Joule per year.

2.2. Case study and data collection

The analysis of conventional POME treatment in open ponds was carried out using information from POME treatment at the palm oil company PT Asam Jawa in North Sumatra, Indonesia. Table 1 compiles some basic features of the studied palm oil mill.

The assessment of the anaerobic digestion of POME is based on data obtained from the experimental anaerobic digestion plant of the Indonesian Oil Palm Research Institute (IOPRI) in North Sumatra, Indonesia. The anaerobic digestion plant is a pilot plant with a total digester volume of 80 m^3. The anaerobic digester operates at mesophilic temperature of 38 °C. The hydraulic retention time (HRT) ranges between 14 and 16 days, and the plants throughput rate is 5 m^3 POME d^{-1}. Table 2 below compiles some basic features of the studied anaerobic digestion plant.

The data and information for this analysis was collected by interviewing plant operators and managers from PT Asam Jawa as well as researchers at IOPRI from July to September 2010 and from August to October 2011.

Table 2
Energy content and GHG emission factors of materials and energy sources. Operational data of the experimental anaerobic digestion plant at IOPRI, North Sumatra, Indonesia.

Factor	Energy content	GHG emission
Diesel fuel	41.33 MJ kg^{-1} (Fritsche and Schmidt, 2001)	87.5 g CO_2-eq kg^{-1} (Fritsche and Schmidt, 2001)
Electricity	–	134.2 g CO_2 MJ^{-1} (Hallman, 2000)
Biochar	28.61 MJ kg^{-1} (Khor et al. 2009)	
Syngas	9.8 MJ kg^{-1} (Khor et al. 2009)	
Bio-oil	36.30 MJ kg^{-1} (Imam and Capareda, 2011)	

Parameter	Unit	Value	Source
Biogas capturing efficiency of digester	%	90	Field data
Electricity generation efficiency	%	30%	UNFCC, 2005
Heat production efficiency	%	30%	UNFCC, 2005
Electricity consumption	$GJ\ yr^{-1}$	336.96	Field data
Diesel fuel consumption for pumping and stirring the POME	$GJ\ yr^{-1}$	269.57	Field data
Energy diesel fuel for additional fuel for the combined heat and power (CHP)	$GJ\ yr^{-1}$	167.88	Field data
Conversion factor	MJ MWh^{-1}	3,599	Waldheim and Nilsson (2001)

2.3. Data analysis

The assessment of the energy balance and GHG emissions from biodiesel production focuses on the contribution of anaerobic POME treatment in a digestion plant to the net energy yield and GHG emissions reduction in comparison with the aerobic POME treatment in open ponds. First, the energy balance and GHG emissions are estimated for the two POME treatment strategies. In a further step, the emissions from the different POME treatment strategies are evaluated against the background of the total energy balance and GHG emissions from biodiesel production using palm oil. For assessing the total energy inputs and outputs as well as GHG emissions from biodiesel production, this study draws on results from Harsono et al. (2011) on the energy balance and GHG emissions from upstream and downstream processes of palm oil based biodiesel production.

2.3.1. Energy balance

The energy balance aims to quantify and present systematically the flow of energy, i.e. the energy produced and consumed along the process of biogas anaerobic digestion, including direct and indirect energy inputs (Angarita et al., 2009; de Souza et al., 2010). The data analysis followed the methodology and algorithms provided by UNFCC (2005). The parameters, data and units used for the assessment are described in the list of abbreviations in Table 3 below.

2.3.2. Energy input

The energy input for the treatment of POME in the anaerobic digester (*E_Input*) includes the electricity for pumping the POME from the open ponds into the digester and for stirring the POME in the digester (Co_{Elec}), the heat energy for regulating the temperature in the anaerobic digester (Co_{Heat}), and the diesel fuel to start the combined heat and power (CHP) plant (Co_{Dsl_fuel}) that converts the methane in the biogas into electricity and heat. The total energy input is calculated according to the Equation (1).

$$E\_Input = Co_{Elec} + Co_{Heat} + Co_{Dsl\_fuel} * EC_{Dsl\_fuel} \tag{1}$$

where:

Co_{Dsl_fuel}: diesel fuel consumption for starting the CHP plant (in $l\ yr^{-1}$)
Co_{Elec}: electricity consumption for POME treatment (in $MJ\ yr^{-1}$)
Co_{Heat}: heat consumption for POME treatment (in $MJ\ yr^{-1}$)
E_Input: energy input (in $MJ\ yr^{-1}$)
EC_{Dsl_fuel}: energy content of diesel (calorific value) (in $MJ\ l^{-1}$)

2.3.3. Energy output

The energy output (*E_Output*) was calculated as the product of the total methane production from POME ($CH_{4\ Prod}$) and the heating value of methane ($CH_{4\ HV}$).

$$E\_Output = CH_{4Prod} * CH_{4HV} * CH_{4Dens} \tag{2}$$

where:

CH_{4Dens}: density of methane (kg CH_4 m^{-3} CH_4)
CH_{4HV}: heating value of methane (in MJ m^{-3} CH_4)
CH_{4Prod}: total methane production (in kg CH_4 yr^{-1})

Table 3
Data used in the calculations for estimating the energy balances and GHG emissions of POME treatment strategies.

Parameter	Description	Unit	Value
AD	% COD degraded in the open ponds	%	9.5[a]
Bio_Prod	Biodiesel production	kg ha^{-1}	4640[h]
$Biogas_{CH4}$	Methane content of biogas	kg CH_4 kg^{-1} biogas	61.97[b]
$Biogas_{Prod}$	Biogas production in a year	kg biogas yr^{-1}	Chapter 3.1[c]
$Biogas_{yield}$	Biogas per unit of organic compounds (COD)	kg biogas kg^{-1} COD	0.56[b]
Bo	Methane per unit of organic compounds (COD)	kg CH_4 kg^{-1} COD	0.21[d]
CH_{4HV}	Methane heating value	MJ m^{-3} CH_4	39.89[g]
CH_{4Loss}	Methane leakage from anaerobic digester	kg CH_4 yr^{-1}	8800 (2%)[b]
CH_{4Prod}	Total methane production	kg CH_4 yr^{-1}	Chapter 3.1[c]
CH_{4Dens}	Density of methane	kg CH_4 m^{-3} CH_4	0.668
COD_{POME}	Chemical Oxygen Demand of POME	kg COD m^{-3} POME	0.114[b]
COD_{Dis}	Chemical Oxygen Demand of discharge POME	kg COD m^{-3} charge	0.006[b]
Co_{Dsl_fuel}	Diesel consumption for starting the CHP plant	MJ yr^{-1}	29[b]
Co_{Elec}	Electricity consumption to pump the POME	MJ yr^{-1}	37[b]
Co_{Heat}	Heat consumption for POME treatment	MJ yr^{-1}	18[b]
DG_{POME}	Share of the POME treated in the digester	%	50[b]
EC_{Bio_fuel}	Energy content of biodiesel (calorific value)	MJ kg^{-1}	41.24[j]
EC_{Dsl_fuel}	Energy content of diesel fuel (calorific value)	MJ l^{-1}	33[i]
$Bio_{Density}$	Densitiy of biodiesel	kg l^{-1}	0.80
E_Input	Total energy input	MJ yr^{-1}	In chapter 3.1[c]
E_Output	Total energy output	MJ yr^{-1}	In chapter 3.1[c]
EF_{Dsl_fuel}	Emission factor for diesel fuel	kg $CO_{2\text{-}eq}$ GJ^{-1}	87.5[f]
EF_{Elect}	Emission factor for grid electricity supply	kg $CO_{2\text{-}eq}$ GJ^{-1}	134.2[e]
EF_{Heat}	Emission factor for heat produced from biogas	kg $CO_{2\text{-}eq}$ GJ^{-1}	77.6[g]
GHG_{Bgs}	Emissions from anaerobic POME treatment	kg $CO_{2\text{-}eq}$ yr^{-1}	In chapter 3.2[c]
$GHG_{Bgs\_\ Elec}$	Emissions from electricity made from biogas	kg $CO_{2\text{-}eq}$ yr^{-1}	In chapter 3.2[c]
GHG_{Bgs_Heat}	Emissions from heat produced using biogas	kg $CO_{2\text{-}eq}$ yr^{-1}	In chapter 3.2[c]
GHG_{BL}	Emissions with POME treatment in open ponds	kg $CO_{2\text{-}eq}$ yr^{-1}	In chapter 3.2[c]
GHG_{Digst}	GHG emissions from anaerobic digester	kg $CO_{2\text{-}eq}$ yr^{-1}	2% of total CH_4[b]
GHG_{Dischr}	Emissions from POME in discharge ponds	kg $CO_{2\text{-}eq}$ yr^{-1}	In chapter 3.2[c]
GHG_{Dsl_fuel}	Emissions from diesel to start the CHP plant	kg $CO_{2\text{-}eq}$ yr^{-1}	In chapter 3.2[c]
GHG_{Pond}	Emissions from POME treated in open ponds	kg $CO_{2\text{-}eq}$ yr^{-1}	In chapter 3.2[a]
GHG_{Pump_Str}	Emissions from electricity to pump the POME	kg $CO_{2\text{-}eq}$ yr^{-1}	In chapter 3.2[c]
GHG_{RED}	Potential reduction of GHG emissions	kg $CO_{2\text{-}eq}$ yr^{-1}	In chapter 3.2[c]
GHG_{Slurry}	Emissions from slurry discharged from digester	kg $CO_{2\text{-}eq}$ yr^{-1}	In chapter 3.2[c]
GWP_CH$_4$	Global warming factor of CH_4	kg $CO_{2\text{-}eq}$ kg^{-1} CH_4	21[d]
MCF_{final}	CH_4 conversion factor in the discharge	%	10[b]
$MCF_{initial}$	CH_4 conversion factor in the first pond	%	62[b]
NEY	Net Energy Yield	GJ yr^{-1}	In chapter 3.1[c]
Q_{Dischr}	Volume of POME discharged per year	m^3 Discharge yr^{-1}	128,018
Q_{POME}	Volume of POME produced in a year	m^3 POME yr^{-1}	234,936[b]

Schuchardt et al. (2008).
Harper (2010).
[a] UNFCC (2005).
[b] Field data.
[c] Own calculation.
[d] IPCC (2006).
[e] Hallmann (2000).
[f] Fritsche and Schmidt (2001)
[g] Turnbull and Kamthunzi (2008).
[h] Harsono et al. (2011).
[i] Commission of the European Communities (2009).
[j] Sivaramakrishnan (2011).

E_Output: energy output (in MJ yr^{-1})

The heating value of methane used in the assessment is 39.89 MJ m^{-3} CH_4 (Engineering Tool Box, 2011). The total methane production (CH_{4Prod}) was calculated as the product of the total biogas production and the methane content in the biogas less the methane losses, as described in the Equation (3).

$$CH_{4Prod} = Biogas_{Prod} * Biogas_{CH_4} - CH_{4Loss} \tag{3}$$

where:

$Biogas_{CH_4}$: methane content in the biogas (in kg CH_4 kg^{-1} biogas)
$Biogas_{Prod}$: quantity of biogas produced (in kg biogas yr^{-1})
CH_{4Loss}: methane leakages from the anaerobic digestion plant (in kg CH_4 yr^{-1})

The methane content of the biogas produced from POME at the IOPRI experimental plant in Medan is 62% (IOPRI, 2011). The total biogas production (*Biogas*$_{Prod}$) was calculated according to the equation (4).

$$Biogas_{Prod} = Q_{POME} * DG_{POME} * COD_{POME} * Biogas_{yield} \tag{4}$$

where:

$Biogas_{yield}$: biogas yield from the COD (in kg biogas kg^{-1} COD).
COD_{POME}: Chemical Oxygen Demand of POME (in kg COD m^{-3} POME)
DG_{POME}: share of the POME treated in the digester (in %)
Q_{POME}: volume of POME produced in a year (in m^3 POME yr^{-1})

The methane in the biogas produced from POME is converted in a CHP plant into electricity and heat. The estimated efficiency of methane conversion into electricity in the CHP plant is 30% (UNFCC, 2005). The remaining energy output of the conversion processes is heat (30%) and energy losses (39%) (UNFCC, 2005). The electricity and heat generated in the CHP plant can be used to cover the energy demand of the anaerobic digestion plant. The surplus energy can serve the palm oil mill and other demands with electricity and heat, including e.g. the energy demand of adjacent communities.

2.3.4. Net energy yield

The net energy yield (*NEY*, in GJ yr^{-1}) is defined as the difference of the energy input and the energy output, as in the Equation (5).

$$\text{Net energy yield} = \text{Energy output} - \text{Energy input} \tag{5}$$

2.3.5. The energy output to energy input ratio

The energy output to energy input ratio is defined as the ratio of the energy output and the energy input according to equation (6).

$$\text{Ratio}_{\text{output}-\text{input}} = \frac{\text{Energy output}}{\text{Energy input}} \tag{6}$$

2.3.6. GHG emission reduction

The potential reduction of GHG emissions (GHG_{RED}) was accounted by subtracting the emissions from anaerobic treatment of POME (GHG_{Bgs}) from the baseline emissions with treatment of POME in open ponds (GHG_{BL}), as in the equation (7).

$$GHG_{RED} = GHG_{BL} - GHG_{Bgs} \tag{7}$$

where:

GHG_{Bgs}: emissions from treatment of POME in anaerobic digester (in kg $CO_{2\text{-eq}}$ yr^{-1})
GHG_{BL}: emissions from the treatment of POME in open ponds (in kg $CO_{2\text{-eq}}$ yr^{-1})
GHG_{RED}: potential reduction of GHG emissions (in kg $CO_{2\text{-eq}}$ yr^{-1})

2.3.7. Baseline emissions

The total baseline emissions from the aerobic treatment of POME in open ponds (GHG_{BL}) were calculated according to the Equation (8). The algorithms to calculate the GHG emissions from the different sources are described in the Equations (9)–(11).

$$GHG_{BL} = GHG_{Pond} + GHG_{Dischr} + GHG_{Pump\_Str} \tag{8}$$

where:

GHG_{Dischr}: emissions from POME discharged after treatment (in kg $CO_{2\text{-eq}}$ yr^{-1})
GHG_{Pond}: emissions from POME stored in open ponds (in kg $CO_{2\text{-eq}}$ yr^{-1})
GHG_{Pump_Str}: emissions from electricity for pumping the POME (in kg $CO_{2\text{-eq}}$ yr^{-1})

The baseline GHG emissions from the POME stored in open ponds (GHG_{Pond}) were calculated according to the Equation (9).

$$GHG_{Pond} = Q_{POME} * COD_{POME} * Bo * MCF_{Initial} * AD * GWP\_\text{CH}_4 \tag{9}$$

where:

AD: percentage of COD degraded in the open ponds (in %)
Bo: methane production capacity (in kg CH_4 kg^{-1} COD)
GWP_CH_4: global warming emission factor of methane (in kg $CO_{2\text{-eq}}$ kg^{-1} CH_4)
$MCF_{Initial}$: methane conversion factor of POME in open ponds (in %)

The $MCF_{Initial}$ factor expresses the proportion of POME anaerobically degraded in the ponds. This is appraised by the difference of COD between the POME before and after the treatment.

The emissions from the POME discharged after the treatment in open ponds (GHG_{Dischr}) were calculated according to the equation (10).

$$GHG_{Dischr} = Q_{Dischr} * COD_{Dis} * Bo * MCF_{final} * GWP\_\text{CH}_4 \tag{10}$$

where:

COD_{Dis}: Chemical Oxygen Demand of discharge (in kg COD m^{-3} POME discharged)
GHG_{Dischr}: emissions from the POME discharged after the treatment (in kg $CO_{2\text{-eq}}$ yr^{-1})
MCF_{final}: methane conversion factor of the POME discharged (in %)
Q_{Dischr}: volume of POME discharged per year (in m^3 POME discharged yr^{-1})

The baseline GHG emissions of electricity for pumping and stirring the POME (GHG_{Pump_Str}) were calculated using the Equation (11).

$$GHG_{Pump\_Str} = Co^{*}_{Elect} EF_{Elect} \tag{11}$$

where:

Co_{Elect}: electricity consumption for pumping and stirring the POME (in GJ yr^{-1})
EF_{Elect}: emission factor for electricity supply from the grid (in kg CO_2 GJ^{-1})

2.3.8. Emissions from anaerobic treatment of POME

The total GHG emissions from anaerobic treatment of POME (GHG_{Bgs}) were estimated as sum of the emissions presented in Equation (12).

$$\begin{aligned} GHG_{Bgs} = {} & GHG_{Pond} + GHG_{Slurry} + GHG_{Bgs\_Heat} + GHG_{Bgs\_Elec} \\ & + GHG_{Digst} + GHG_{Dischr} + GHG_{Pump\_Str} + GHG_{Dsl\_fuel} \end{aligned} \tag{12}$$

where:

GHG_{Bgs}: emissions from anaerobic treatment of POME (in kg $CO_{2\text{-eq}}$ yr^{-1})
GHG_{Bgs_Elec}: emissions from electricity generated from biogas (in kg $CO_{2\text{-eq}}$ yr^{-1})
GHG_{Bgs_Heat}: emissions from heat needed for temperature regulation (in kg $CO_{2\text{-eq}}$ yr^{-1})
GHG_{Digst}: emissions (leakages) from the anaerobic digestion plant (in kg $CO_{2\text{-eq}}$ yr^{-1})
GHG_{Dischr}: emissions from the POME discharged from the ponds (in kg $CO_{2\text{-eq}}$ yr^{-1})
GHG_{Dsl_fuel}: emissions from fuel used to start-up the CHP plant (in kg $CO_{2\text{-eq}}$ yr^{-1})
GHG_{Pond}: emissions from POME treated in open ponds (in kg $CO_{2\text{-eq}}$ yr^{-1})

GHG_{Pump_Str}: emissions from electricity for pumping the POME (in kg $CO_{2\text{-eq}}$ yr^{-1})
GHG_{Slurry}: emissions from slurry discharged from the digester (in kg $CO_{2\text{-eq}}$ yr^{-1})

The estimation of the emissions from the POME that continues to be treated in open ponds (GHG_{Pond}), the POME discharged from the open ponds (GHG_{Dischr}), the slurry discharged from the anaerobic digester after the treatment (GHG_{Slurry}) and the electricity for pumping and stirring the POME (GHG_{Pump_Str}) was made using the same algorithms as for the calculation of the baseline emissions described in the Equations (8)–(11). The GHG emissions from heat to regulate the temperature in the digester (GHG_{Bgs_Heat}) were calculated according to Equation (13).

$$GHG_{Bgs\_Heat} = Co_{Heat} * EF_{Heat} \tag{13}$$

where:

Co_{Heat}: heat consumed in a year to regulate the temperature in the digester (in GJ yr^{-1})
EF_{Heat}: emission factor for heat generated from biogas (in kg $CO_{2\text{-eq}}$ GJ^{-1})

The GHG emissions from diesel fuel for starting the CHP plant (GHG_{Dsl_fuel}) were calculated according to Equation (14).

$$GHG_{Dsl\_fuel} = Tot_{Dsl\_fuel} * EC_{Dsl\_fuel} * EF_{Dsl\_fuel} \tag{14}$$

where:

EC_{Dsl_fuel}: energy content of biodiesel by volume (lower calorific value) (in GJ l^{-1})
EF_{Dsl_fuel}: emission factor of diesel fuel (in kg $CO_{2\text{-eq}}$ GJ^{-1})
Tot_{Dsl_fuel}: total diesel fuel consumed to start the CHP plant in a year (in l yr^{-1})

3. Results and discussion

3.1. Energy balances

3.1.1. Energy input

The energy input for the treatment of POME in the anaerobic digester totals 1092 GJ yr^{-1}, or 0.08 GJ ha^{-1} yr^{-1}. The largest energy input is for pumping and stirring the POME (44%), followed by the energy input from diesel fuel for starting the CHP plant (35%), and the energy input for regulating the temperature in the anaerobic digester (21%). The energy balances is shown in Table 4 below.

Table 4
Energy input, energy output, net energy yield and energy output to energy input ratio of covered ponds of POME treatment in a digestion plant in Sumatra, Indonesia (in MJ ha^{-1} yr^{-1}).

Parameter	Unit	Value
Energy input		
Electricity for pumping and stirring POME	MJ ha^{-1} yr^{-1}	37
Diesel fuel to start-up the CHP plant	MJ ha^{-1} yr^{-1}	29
Diesel fuel for temperature regulation	MJ ha^{-1} yr^{-1}	18
Total energy input (a)	MJ ha^{-1} yr^{-1}	84
Total energy output (electricity and heat) (b)	MJ ha^{-1} yr^{-1}	2021
Net energy yield (b − a)	MJ ha^{-1} yr^{-1}	1937
Energy output to energy input ratio (b/a)*		23.1

Table 5
Total baseline emissions for aerobic treatment of POME in open ponds (GHG_{BL}) (in kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}).

Emission source	Unit	Value
POME stored in open cooling ponds (GHG_{Pond})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	6956.78
POME in discharge ponds (GHG_{Dischr})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	621.64
Electricity supply from the grid (GHG_{Pump_Str})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	4.97
Total baseline emissions (GHG_{BL})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	7583.39

3.1.2. Energy output

The amount of biogas produced from POME in the studied anaerobic digestion plant is 710 t biogas yr^{-1}. This is equivalent to a methane production of 440 t CH_4 yr^{-1} and an energy output of 26,275 GJ yr^{-1}, or 2.02 GJ ha^{-1} yr^{-1}, based on a heating value of methane of 39.89 MJ m^{-3} CH_4 (i.e. 59.72 MJ kg^{-3} CH_4) and a plantation area of 13,000 ha. The estimated energy output is higher compared with the results from other studies as Sousa et al. (2010) written in their report. They have shown that Yusoff and Hansen (2007) and Yee et al. (2009) estimated an energy output from the anaerobic digestion of POME of 1.72 GJ ha^{-1} yr^{-1} Pleanjai and Gheewala (2009) calculated an energy output of 1.54 GJ ha^{-1} yr^{-1}, and de Souza et al. (2010) reported an energy output of 1.85 GJ ha^{-1} yr^{-1}.

3.1.3. Net energy yield

The net energy yield of the anaerobic treatment of POME in the studied case is 1.94 GJ ha^{-1} yr^{-1} as seen in Table 4 above. The energy consumption of the anaerobic digestion of 0.08 GJ ha^{-1} yr^{-1} is equivalent to 4.2% of the total energy output from biogas. The surplus energy output from the anaerobic treatment of POME can be used to cover the total energy demand of the palm oil mill of 1.21 GJ ha^{-1} yr^{-1} (Harsono et al., 2011).

3.1.4. Energy output to energy input ratio

The energy output to energy input ratio of POME treatment in anaerobic digestion is 23.1 in the studied case. The net energy yield may further be increased by treating higher shares of POME in the anaerobic digestion plant. However, in many peripheral areas it may be difficult to use the surplus of energy purposefully, e.g. if adjacent communities do not have access to electricity from the grid.

Table 6
Emissions with covered ponds of POME in the digestion plant (in kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}).

Emission source	Unit	Value
POME stored in open cooling ponds (GHG_{Pond})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	3478.39
Diesel fuel used to start the CHP plant (GHG_{Dsl_fuel})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	389.81
POME in discharge ponds (GHG_{Dischr})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	310.82
Slurry discharged from digestion plant (GHG_{Slurry})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	310.82
Electricity supply from the biogas (GHG_{Bgs_Elec})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	13.19
Heat supply from the biogas (GHG_{Bgs_Heat})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	11.56
Leakages from the digestion plant (GHG_{Digst})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	10.08
Electricity supply from the grid (GHG_{Pump_Str})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	4.97
Total emissions from anaerobic treatment (GHG_{Bgs})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	4529.64

3.2. GHG emissions

3.2.1. Baseline GHG emissions from aerobic treatment of POME in open ponds

The total GHG emissions from the aerobic treatment of POME in open ponds amount to 7583 kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1} as shown in Table 5 below. The largest share of the GHG emissions comes from the POME stored in the open ponds (91.7%), followed by the emissions from the POME discharged (8.2%) and the emissions from the generation of electricity for pumping and stirring the POME (0.1%). The GHG emission is shown in Table 5 below.

Related to the unit of biodiesel, the total GHG emissions from the treatment of POME in open ponds are 1634 g $CO_{2\text{-eq}}$ kg^{-1} biodiesel, based on a biodiesel yield of 4640 kg ha^{-1} yr^{-1}. This is equivalent to 39.63 g $CO_{2\text{-eq}}$ MJ^{-1} biodiesel, based on an energy content of palm oil biodiesel of 41.24 MJ kg^{-1} (Sivaramakrishnan, 2011). Choo et al. (2011) estimated GHG emissions of 33.19 g $CO_{2\text{-eq}}$ MJ^{-1} biodiesel without methane capture only.

3.2.2. GHG emissions from anaerobic treatment of POME in digestion plant

In the studied case with anaerobic treatment of 50% of the POME the GHG emissions amount to 4530 kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1} as shown in Table 6 below. Related to the functional unit, the GHG emissions in the case with anaerobic treatment of POME are 976 g $CO_{2\text{-eq}}$ kg^{-1} biodiesel produced. This is equivalent to 23.67 g $CO_{2\text{-eq}}$ MJ^{-1} biodiesel. Choo et al. (2011) estimated GHG emissions of 21.72 g $CO_{2\text{-eq}}$ MJ^{-1} biodiesel with methane capture only.

In this study shows, that even only 50% of the POME is used in a biogas digester, the methane output is higher than in the cases described by Choo et al. (2011), where the methane is captured using covered ponds. Consequently, there is a significant efficiency gain in the treatment of POME in biogas digesters instead of only covering the open ponds. This is shown in Table 6 below.

The shares of the total GHG emissions include the emissions from the POME that continues to be stored and treated in open ponds (76.8%), POME and slurry discharged from the open ponds and the digestion plant (13.8%), fuel used to start-up the CHP plant (8.6%), emissions from the generation of electricity and heat required in the process (0.5%), GHG leakages from the digester (0.2%) and electricity for pumping the POME (0.1%). Further emission reductions may be achieved by increasing the share of POME treated in the anaerobic digestion plant, since POME treated in the open ponds is still the major source of GHG emissions. Another option is to mix the unexploited POME with chopped EFB to produce an organic fertilizer (Stichnothe and Schuchardt, 2010). This treatment further contributes to reduce GHG emissions from POME and to recycle the nutrients contained in the palm oil mill residues.

Table 7
GHG emissions from biodiesel production with aerobic POME treatment in open ponds compared to biodiesel production with anaerobic POME treatment in an anaerobic digester.

Parameter	Unit	POME treatment practices	
		Open ponds	Covered ponds
Emissions from biodiesel production	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	1566.00[a]	1566.00[a]
Emissions from POME treatment	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	7583.39[b]	4529.64[c]
Total emissions from biodiesel production including POME treatment	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}	9149.39	6095.64
Difference of GHG emissions (GHG_{RED})	kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}		3053.75
Reduction of GHG emissions	%		33.38
Reduction of GHG emissions[d]	g $CO_{2\text{-eq}}$ kg^{-1} biodiesel		658.14
Reduction of GHG emissions[e]	g $CO_{2\text{-eq}}$ MJ^{-1} biodiesel		15.96

Remarks.
[a] Harsono et al. (2011:12).
[b] See Table 5.
[c] See Table 6.
[d] 1 ha of land yields 4640 kg of biodiesel.
[e] Energy content of palm oil biodiesel: 41.24 MJ kg^{-1} (Sivaramakrishnan, 2011).

3.2.3. GHG emission reduction

The GHG emission reduction is estimated as the difference of the GHG emissions from aerobic treatment of POME in open ponds (Table 5) and the emissions from anaerobic treatment of POME in the digestion plant (Table 6). Table 7 below shows the potential contribution of the anaerobic treatment of POME to reduce the GHG emissions from palm oil biodiesel production, if 50% of the POME is treated in the digestion plant. It is shown in Table 7 below.

The emissions from the POME stored and treated in open ponds amount to 83% of the total GHG emissions from palm oil biodiesel production. The remaining 17% of the GHG emissions accrue from the milling and manufacturing of the palm oil biodiesel.

In the studied case, the aerobic treatment of POME in open ponds causes about 67% higher GHG emissions than the anaerobic treatment of POME in a digestion plant. Against the background of the total GHG emissions from palm oil based biodiesel production, the aerobic treatment of POME in open ponds results in 50% higher GHG emissions than the anaerobic treatment of POME in a digestion plant in the studied case.

The saving of GHG emissions using anaerobic treatment of POME in a digestion plant instead of aerobic treatment in open ponds is 3054 kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}. This represents a reduction in GHG emissions of 33% compared to the baseline GHG emissions with aerobic treatment of POME in open ponds as shown in Table 7 above. The emission reduction amounts to 658 g $CO_{2\text{-eq}}$ kg^{1} biodiesel or nearly 15.96 g $CO_{2\text{-eq}}$ MJ^{-1} biodiesel. As to be expected, this result is higher than the emission savings with only capture of methane of about 11.99 g $CO_{2\text{-eq}}$ MJ^{-1} biodiesel reported by Choo et al. (2011).

4. Conclusion

The growing production of palm oil biodiesel in Indonesia has led to increasing amounts of POME, a highly polluting wastewater residue from the milling process in palm oil production. The anaerobic treatment of POME is a source of renewable energy, and it offers the possibility to significantly reduce the GHG emissions from palm oil biodiesel production. In the studied case, the estimated energy output from POME treatment in the anaerobic digester is 0.44 MJ kg^{-1} biodiesel, and the net energy yield is 0.42 MJ kg^{-1} biodiesel. The ratio of energy output to energy input of the anaerobic treatment of POME is positive (23.1). The methane obtained from the anaerobic digestion can be converted into electricity and heat, and substitute non-renewable fossil fuels used in biodiesel production.

The estimated reduction of GHG emissions is 658 g $CO_{2\text{-eq}}$ kg^{-1} biodiesel, or nearly 16 g $CO_{2\text{-eq}}$ MJ^{-1} biodiesel. In the studied case, the total GHG emissions from biodiesel production are reduced by about 33% applying anaerobic treatment of POME in a digestion plant. The GHG emissions can be reduced further by increasing the amount of POME treated in anaerobic digestion plants, and using the energy in the biogas to replace fossil fuels. The efficient use of the surplus energy obtained from the biogas is a precondition to achieve a high reduction of GHG emissions. We conclude that the anaerobic treatment of POME can make a significant contribution toward meeting international targets of emissions reduction for biodiesel production. This motivation needs to be geared to generate solutions and realize investments for fully exploiting the energy potential and GHG savings from POME treatment in anaerobic digestion plants.

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