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# Energy generation from palm oil mill effluent: A life cycle assessment of two biogas technologies

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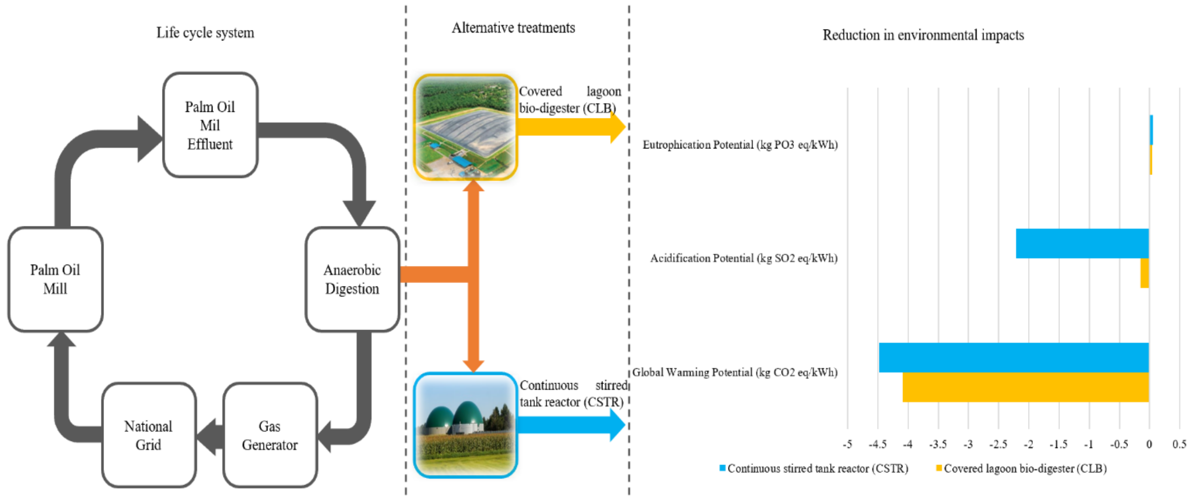
## GRAPHICAL ABSTRACT



## ABSTRACT

This study conducted a life cycle assessment of palm oil mill effluent (POME) based energy generation using the CML 2001 method and Gabi 8 software, focusing on two POME treatment technologies: the covered lagoon bio-digester (CLB) and the continuous stirred tank reactor (CSTR). The analysis determined the respective environmental impacts of the technologies, both of which are currently in use in Malaysia. The global warming potential (GWP) and acidification potential (AP) for CSTR were -4.48 kg $CO_2$ eq/kWh and -2.21 kg $SO_2$ eq/kWh respectively, while for CLB the values were -4.09 kg $CO_2$ eq/kWh and -0.15 kg $SO_2$ eq/kWh. Both technologies produced a negative result, which equates to a net environmental benefit. However, both systems had a negative impact in terms of eutrophication potential (EP). The CSTR nevertheless achieved a better EP result of 0.048 kg $PO_4^{3-}$eq/kWh than the CLB with 0.054 kg $PO_4^{3-}$eq/kWh. A sensitivity analysis was carried out in order to find a way to overcome the impacts of EP. The findings provide useful data to guide decision-makers in the sustainable management of POME, in Malaysia and globally where similar technologies are in use.

Keywords: POME, Anaerobic digester, Global warming potential, Acidification potential Eutrophication potential

# 1. Introduction

In Malaysia, 5.8 million hectares of land are covered by oil palm plantations [1] and there are approximately 454 palm oil mills (POMs) in operation [2]. Each oil palm produces 8 to 15 fresh fruit bunches (FFBs) annually [3]. Oil extracted from these FFBs consists of 10% of the whole dry matter of the palm, while the remaining 90% is palm oil biomass [4], comprising empty fruit bunches (EFBs), palm oil mill effluent (POME), mesocarp fibres, palm kernel shells, and palm oil trunks and fronds [5,6]. Both POME and EFBs are generated in huge quantities [7]. POME is a non-toxic, thick, viscous liquid waste that can cause damage if it is directly released into the environment as it is a highly polluting wastewater [8].

POME has high organic content. An anaerobic treatment method is thus most suitable because such a method is more efficient [9]. Anaerobic digestion (AD) is currently considered the most environmentally friendly biological treatment process because the waste subjected to AD can be converted into value-added products such as bio-energy [10]. In the biodegradation step, a high-rate bioreactor is effective because it can produce a high methane yield within a relatively short retention time while tolerating the operating and capital costs [9].

One of the types of AD system is the fluidised bed reactor (FBR), which requires a large surface area for biomass attachment and mass transfer. The FBR is usually employed in treatment of high-strength wastewater [11]. However, the process requires highly turbulent conditions, which result in higher energy consumption. Also, the media in the reactor, which can be costly, has to be well maintained to sustain the efficiency of the system. Bacteria tend to adhere to the reactor bed due to the intensive conditions in the system. Unfortunately, this system is not efficient in terms of capturing the biogas produced [12]. A further type of AD system is the up-flow anaerobic sludge blanket (UASB) reactor, which does not require any media for the treatment of wastewater with high suspended solids. While the UASB reactor is an efficient system in terms of removing chemical oxygen demand (COD), it produces an increased amount of methane emissions in doing so. The system also has a tendency to retain a high concentration of biomass within the reactor itself [12]. The other main disadvantage of using the UASB reactor is that it has a very poor ability to separate biomass and treated effluent. On the plus side, the UASB reactor consumes a low amount of energy [13].

The UASB reactor can be combined with an up-flow fixed film (UFF) reactor to create an up-flow anaerobic sludge fixed film (UASFF) reactor [12]. The UASB reactor has a low energy demand, so the UASFF offers an improved version of both the UASB and UFF reactors. However, while it has a good process control system, it still has a very poor ability to separate effluent and biomass, resulting in very poor efficiency [14]. A further type of bed reactor is the expanded granular sludge bed (EGSB) reactor, which is based on a modification of the hydrodynamics of the UASB reactor [10]. The EGSB reactor is efficient in the removal of COD. It performs better with an average organic loading rate (OLR) compared to the UASB which performs best at a low OLR. Most of the biological and chemical reactions proceed much more slowly under psychrophilic conditions, resulting in more energy consumption compared to mesophilic conditions [15]. According to recent research [16], the EGSB reactor performs comparably under both conditions. Nevertheless, the EGSB reactor has two main disadvantages: the inability of the granular bed to retain suspended solids and its requirement for the installation of active biomass for granular anaerobic sludge [12].

One of the most common AD methods is the covered lagoon bio-digester (CLB), applied by the majority of the POMs with biogas facilities in Malaysia. It is considered a simple and stable operating system that is also capable of tolerating a high OLR. The two main disadvantages of this system are the large area of land it needs and the long hydraulic retention time required to produce the biogas [12]. Conversely, this system consumes a very low amount of energy and has low operating costs [17]. The CLB is one of the two treatment technologies evaluated in this study.

The other type of technology evaluated in this study is the continuous stirred tank reactor (CSTR), one of the commercialised AD systems used in most of the POMs employing the tank system. It is very cheap and relatively easy to construct. The system has a good mixing ability, which enhances the contact area between the biomass and wastewater [18]. The CSTR system has lower operating costs than some of the other systems because a low amount of energy is consumed. However, the operation can be time consuming and there is very low biomass retention [12]. Few of the AD systems, for example, CLB, CSTR and UASB have been commercialised in POMs in Malaysia. UASB is still under consideration and not solely utilised for energy generation, while the remaining AD systems are still under observation at a lab scale.

The present study uses a life cycle assessment (LCA) approach to quantify the environmental impacts of two different POME treatment technologies. The research builds on previous investigations that use LCA to evaluate different environmental indicators for energy generation from POME. LCA is a tool that can be used to evaluate the environmental impact of a product from its formation stage or the extraction of natural resources (cradle) until its complete degradation in the environment or end of life (grave) [19]. Most existing LCA studies have compared a biogas technology with a composting system [20,21] or have conducted analyses of combinations of the open lagoon system with biogas and composting facilities [22].

Environmental impact assessments for different treatment scenarios for palm oil production waste have been published previously [20]. Key scenarios and findings are summarised from this below. The scenarios for comparison are: (a) dumping EFB and storing POME and ponds, (b) returning EFB to the plantation and POME as before, (c) using EFB and POME for co-composting and returning the produced compost to the plantation, (d) generating biogas from POME and followed by (c). Findings from analyses by [20] showed that the major contributor to the GWP is the methane emission upon dumping the POME and EFB. Nutrient recycling and reduced methane emissions can decrease the GWP value from 245 kg $CO_2$ eq to up to 5 kg $CO_2$ eq per ton FFB. For instance, co-composting EFB and POME leads to reduction in GWP and considered as nutrient recovery. Therefore, composting helps in simultaneously reducing the environmental burdens and gaining net environmental benefit. The best option with reduced environmental impact would be co-composting of EFB and POME, with or without treating POME in a biogas plant as this way could make use the nutrients of both the palm oil residues.

In other studies, environmental impacts of six alternatives for the conversion of 30 t/h of FFBs into biorefineries have been assessed [21]. Alternative scenarios that were assessed were: production of biogas from the POME (C1), composting of EFB and fibre (C2), biomass combustion for high pressure steam CHP (C3), pellet production (C4), biochar production (C5), and biochar and bio-oil production (C6). With respect to GHG emissions, reductions of >33% were found to be achieved, while composting and anaerobic digestion reduced the EP value by 30%. As a whole, the most preferred alternative was the pellet production biorefinery.

LCA studies have been conducted by [22] for a combination of open lagoon technology (COLT) with composting and COLT-Biogas for POME treatment. COLT-Biogas technology comprises: composting (A), land application (B) and membrane technology (C). The most environmentally friendly technology was COLT-Biogas A as this technology was able to emit 357.18 kg $CO_2$ eq less than the other treatment processes with respect to GWP. With respect to EP, COLT-Biogas A and COLT-Composting result in zero EP as no nitrification of the water or land occurs with the use of these technologies. The highest EP of 7.73 kg $PO_4^{3-}$eq was observed for the open lagoon technology, followed by COLT-Biogas B, with EP of 6.14 kg $PO_4^{3-}$eq, and COLT-Biogas C, with EP of 5.96 kg $PO_4^{3-}$eq. The highest value of AP was mainly observed in COLT-Biogas A, where turning and moving the EFB in the composting area used diesel, resulting in the contribution of approximately 55% of the AP value. HTP emissions were negligible in this study because the palm oil mill's processing was not within the system boundary. As a whole, the lowest energy consumption was by COLT-Biogas C, while the highest net energy ratio (NER) was observed for COLT-Biogas B and COLT-Biogas C. The technology with the lowest EP and GWP values was COLT-Biogas A, while COLT-Biogas B and COLT-Biogas C had the lowest AP values [22].

The present study builds on this previous work. Our main objective was to use a LCA to quantify the environmental impacts of two different POME treatment technologies. The environmental impact and the amount of sludge used for composting purposes is discussed in section 3.4 (sensitivity analysis). Sensitivity analysis performed in this study evaluates the EP impacts after the application of a composting system to the existing biogas system for electricity generation. This adds to the novelty as the boundary of this study does not include the composting system. The results offer useful information to decision-makers and planners for biogas projects in existing POMs without such facilities. Findings can also guide the implementation of biogas facilities in new POMs.

## 2. Methodology

One of the best ways to assess the environmental performance of POME-based energy generation is to use LCA. A LCA generally consists of four parts: i) goal and scope definition, ii) inventory analysis, iii) impact assessment, and iv) interpretation. In addition, an analysis of the sensitivity of the parameter that has the most effect on the life cycle emissions is undertaken in this study. The next section provides an overview of the CLB and CSTR set-ups that we evaluate. We then describe our methods in relation to the four parts of the LCA and the sensitivity analysis.

### *2.1. Overview of the two compared POME treatment technologies for energy generation*

The CLB and CSTR that were evaluated in this study are located at two different POMs, which for the purpose of this study are named POM 1 and POM 2.

The CLB in POM 1 is an improvement on the conventional system- the open ponding system. First, the POME from the mill is directed to the cooling pond in order to stabilise the temperature of the inlet wastewater before it enters the CLB system. This is to ensure the maintenance of optimal conditions (pH and temperature) in the digester and thereby ensure that the system yields the highest efficiency in terms of organic material decomposition. POME from the cooling pond is channelled to mixing ponds and then pumped into the digester where the majority of the decomposition takes place. The CLB is covered with a non-permeable high-density polyethylene (HDPE) membrane and a geotextile is set over the slope of the pond to fully enclose the digester system. The biogas that is generated is extracted from below the HDPE membrane and directed to the scrubber and chiller. The POME digestate from the anaerobic digester is directed to facultative ponds to further reduce the level of biological oxygen demand (BOD), before discharging digestate POME for land application. The biogas generated is purified and combusted in gas engines to generate electricity, and supplied to the national grid. The sludge obtained from the digester is used for composting purposes.

The CSTR at POM 2 is another AD system that has been implemented in POMs in place of the conventional system- the open digesting tank. First, the POME from the mill is channelled to the de-oiling tank for the removal of 90% of the oil. Then, the POME is directed into a cooling pond to reduce its temperature to about 50 °C. The POME is then stored in the distribution tank before being directed to the digester tanks for AD to take place. The top of the tank is covered to trap the biogas. POME is fed continuously into the digester under appropriate mixing and circulation conditions inside the tank. The digestate POME and generated biogas is stored in a holding tank. The digestate POME undergoes further treatment as it passes through anaerobic and aerobic ponds before it is used for land application. The generated biogas is purified before being combusted in gas engines to supply the national grid. The sludge obtained from the digester is used for composting purposes.

### *2.2. Life cycle assessment (LCA)*

The LCA software Gabi 8 was used to evaluate the environmental impacts of inventory elements and life cycles for our two scenarios. This subsection sets out the goal, scope, functional unit, system boundaries, assumptions, and impact assessment.

The aim of this study was to assess and compare the environmental impacts of energy generation from POME in the context of Malaysia by comparing two different POME treatment technologies: CLB and CSTR systems. The main goal was to evaluate the potential environmental benefits of employing two different POME treatment technologies to determine which treatment technology was most environmentally friendly. Two POMs located in two different states of Malaysia were used as case studies. A gate-to-gate LCA was undertaken to quantify and compare the environmental impact of the CLB and CSTR systems. The LCA therefore covered all the stages of the process of energy generation from POME, beginning with the transfer of the POME from the POM, through pre-treatment before entry to the AD system, production of biogas in AD, purification of the biogas generated, combustion of the biogas in the gas engine for energy generation and finally, treatment of the effluent, before discharging it for land application. The environmental impact of every process was taken into consideration. In this study, 1 kWh of electricity generated from POME was used as the functional unit because this enabled easy comparison of the two technologies.

All data on the inputs and outputs to the Gabi 8 software were directly obtained from the POMs. Data were normalised to the functional unit of 1 kWh of electricity generation for easy comparison between the two different treatment technologies. It was, however, necessary to calculate the emissions (output), as the databases available in Gabi 8 did not represent the scenarios investigated by this study. The default emission factor values listed in Table 1 were obtained from the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories [23] while the grid displacement value was obtained from the latest report of the Clean Development Mechanism (CDM) electricity baseline 2014 [24]. Moreover, [25] report a range of methane correction factors, so a suitable value based on the scenario had to be used. Most of the mills with biogas systems in Malaysia follow the IPCC guidelines to calculate carbon emissions for CDM applications. The CDM has played a great role in encouraging a massive reductions of $CO_2$ eq over the years, helping to mitigate climate change [26]. External data such as discharge of digestate POME for land application and usage of sludge for composting purposes were not taken into consideration as these did not fall within the system boundaries. Efficiency for both the CLB and CSTR systems was assumed to be 90% based on a report by [27] and information obtained directly from both the POMs. The mass and energy balances inclusive of every input and output flow are listed in Table 2.

**Table 1** Emission and conversion factors

| Description | Symbol | Unit | Value | Reference |
|---|---|---|---|---|
| **Emission factor** | | | | |
| Global warming potential | $WP_{CH_4}$ | kg $CO_2$ eq/kg $CH_4$ | 21 | [23] |
| Grid displacement | $EF_{CO_2}$ | kg $CO_2$ eq/kWh | 0.694 | [24] |
| $PO_4$ equivalence factor (eutrophication | $P_{o,cod}$ | kg $PO_4^{3-}$eq/kg COD | 0.022 | [22] |
| potential) | $P_{o,tn}$ | kg $PO_4^{3-}$eq/kg N | 0.42 | [28] |
| $SO_2$ equivalence factor (acidification potential) | $S_{o,ww}$ | kg $SO_2$ eq/kg $H_2S$ | 1.88 | [22] |
| Methane production per kg COD digester | $B_{o,ww}$ | kg $CH_4$/ kg COD | 0.21 | [23] |
| **Methane correction factor** | | | | |
| Digester efficiency | $CFE_{ww}$ | | 0.9 | [27] |
| Digestate POME | $MCF_{ww,digestate}$ | | 0.1 | [25] |
| Recovery/combustion utilisation | $MCF_{ww,anaerobic}$ | | 1.0 | [25] |

**Table 2** Inventory for CLB and CSTR (functional unit = 1 kWh of electricity)

| | Unit | CLB | CSTR |
|---|---|---|---|
| **Inputs** | | | |
| POME production | $m^3$ | 0.028 | 0.020 |
| **Electricity** | | | |
| Transfer pump | kWh | 0.038 | 0.034 |
| Blower | kWh | 0.0018 | - |
| Mixer | kWh | - | 0.13 |
| Scrubber | kWh | 0.00075 | 0.0367 |
| Chiller | kWh | 0.001 | 0.012 |
| Booster fan | kWh | - | 0.0075 |
| **Processes** | | | |
| Biogas production | $m^3$ | 0.50 | 0.60 |
| **Outputs** | | | |
| Electricity | kWh | 1 | 1 |
| Sludge (used for composting purposes) | kg | 1.6667 | 1.6667 |
| **Emissions** | | | |
| $CO_2$ emissions | | | |
| Open pond | kg $CO_2$ eq | 0.01 | 0.08 |
| Biogas captured (reduction) | kg $CO_2$ eq | -4.13 | -4.71 |
| $SO_2$ emissions | | | |
| Biogas captured (reduction) | kg $SO_2$ eq | -0.15 | -2.21 |
| $PO_4$ emissions | | | |
| COD in POME | kg $PO_4^{3-}$eq | 0.051 | 0.040 |
| N in POME | kg $PO_4^{3-}$eq | 0.0032 | 0.0081 |
| $CO_2$ emissions from electricity | | | |
| Transfer pump | kg $CO_2$ eq | 0.026 | 0.024 |
| Blower | kg $CO_2$ eq | 0.0012 | - |
| Mixer | kg $CO_2$ eq | - | 0.090 |
| Scrubber | kg $CO_2$ eq | 0.00052 | 0.025 |
| Chiller | kg $CO_2$ eq | 0.00069 | 0.0083 |
| Booster fan | kg $CO_2$ eq | - | 0.0052 |

The equations applied to quantify the investigated emissions were modified based on the CDM methodology booklet [29]. The following equations were applied to calculate the emissions contributing to GWP:

$$\mathrm{WP} = \mathrm{E}_{\mathrm{h,power}} + \mathrm{E}_{\mathrm{h,anaerobic,ww}} + \mathrm{E}_{\mathrm{h,ww,digestate}} \tag{1}$$

$$\mathrm{E}_{\mathrm{h,power}} = \mathrm{E}_{\mathrm{h,elec}} \times \mathrm{EF}_{\mathrm{CO_2}} \tag{2}$$

$$\mathrm{E}_{\mathrm{h,anaerobic,ww}} = (1 - \mathrm{CFE}_{\mathrm{ww}}) \times \mathrm{MEP}_{\mathrm{h,ww,treatment}} \times \mathrm{WP}_{\mathrm{CH_4}} \tag{3}$$

$$\mathrm{E}_{\mathrm{h,ww,digestate}} = \mathrm{MEP}_{\mathrm{h,ww,digestate}} \times \mathrm{WP}_{\mathrm{CH_4}} \tag{4}$$

where $E_{h,power}$ is the emissions from the energy generated (kg $CO_2$ eq); $E_{h,elec}$ is the amount of energy used (kWh); $EF_{CO2}$ is the emission factor for grid displacement (kg $CO_2$ eq/kWh);

$E_{h,anaerobic,ww}$ is the emission from the wastewater of the anaerobic treatment system (kg $CO_2$ eq); $CFE_{ww}$ is the methane correction factor for the anaerobic digester; $MEP_{h,ww,treatment}$ is the methane emission from the wastewater upon treatment (kg $CH_4$); $GWP_{CH4}$ is the emission factor for GWP (kg $CO_2$ eq/kg $CH_4$); $E_{h,ww,digestate}$ is the emission from the digestate POME (kg $CO_2$ eq); and $MEP_{h,ww,digestate}$ is the methane emission from the digestate POME (kg $CH_4$).

As regards $MEP_{h,ww,treatment}$, which is the methane emission from the wastewater upon treatment and $MEP_{h,ww,digestate}$, which is the methane emission from the digestate POME, these can be expressed, respectively, as:

$$\mathrm{MEP}_{\mathrm{h,ww,treatment}} = \mathrm{Q}_{\mathrm{h,ww}} \times \mathrm{COD}_{\mathrm{h,ww,treated}} \times \mathrm{B}_{\mathrm{o,ww}} \times \mathrm{MCF}_{\mathrm{ww,anaerobic}} \tag{5}$$

$$\mathrm{MEP}_{\mathrm{h,ww,digestate}} = \mathrm{Q}_{\mathrm{h,ww}} \times \mathrm{COD}_{\mathrm{h,ww,digestate}} \times \mathrm{B}_{\mathrm{o,ww}} \times \mathrm{MCF}_{\mathrm{ww,digestate}} \tag{6}$$

where $Q_{h,ww}$ is the flow rate of the wastewater ($m^3$); $COD_{h,ww,treated}$ is the digested amount of COD based on the difference between the initial COD input and final COD output of the particular process (kg $COD_{treated}/m^3$); $B_{o,ww}$ is the methane production per kg of COD digested (kg $CH_4$/kg COD); $MCF_{ww,anaerobic}$ is the methane correction factor for recovery utilisation; $COD_{h,ww,digestate}$ is the value of the digestate COD for the respective process (kg $COD_{digestate}/m^3$); and $MCF_{ww,digestate}$ is the methane correction factor for the digestate POME.

In this study, sulphur dioxide generation was considered to be the major contributor to AP, where the acidifying effect can be expressed as:

$$\mathrm{AP} = \mathrm{E}_{\mathrm{h,sulphur\ dioxide,ww}} \tag{7}$$

$$\mathrm{E}_{\mathrm{h,sulphur\ dioxide,ww}} = (1 - \mathrm{CFE}_{\mathrm{ww})} \times \mathrm{H_2S}_{\mathrm{h,generated}} \times \mathrm{S}_{\mathrm{o,ww}} \tag{8}$$

where $E_{h,sulphur\ dioxide,ww}$ is the emission of sulphur dioxide from the wastewater of the anaerobic treatment system (kg $SO_2$ eq); $H_2S_{h,generated}$ is the amount of hydrogen sulphide gas generated (kg $H_2S$); and $S_{o,ww}$ is the $SO_2$ equivalence factor related to the AP impact (kg $SO_2$ eq/kg $H_2S$).

Eutrophication potential was calculated based on the availability of total nitrogen and phosphorus content. Based on the industrial data, only COD and total nitrogen in the POME were observed to contribute to phosphate emissions, which were calculated as follows:

$$\mathrm{EP} = \mathrm{E}_{\mathrm{h,phosphate,ww,cod}} + \mathrm{E}_{\mathrm{h,phosphate,ww,tn}} \tag{9}$$

$$\mathrm{E}_{\mathrm{h,phosphate,ww,cod}} = \mathrm{COD}_{\mathrm{h,ww,pome}} \times \mathrm{P}_{\mathrm{o,cod}} \tag{10}$$

$$\mathrm{E}_{\mathrm{h,phosphate,ww,tn}} = \mathrm{TN}_{\mathrm{h,ww,pome}} \times \mathrm{P}_{\mathrm{o,tn}} \tag{11}$$

where $E_{h,phosphate,ww,cod}$ represents the emissions from the wastewater of the anaerobic treatment system due to the presence of COD in the POME (kg $PO_4^{3-}$eq); $COD_{h,ww,pome}$ is the amount of COD in the POME (kg COD); $P_{o,cod}$ is the $PO_4^{3-}$ equivalence factor contributing to the EP impact due to COD (kg $PO_4^{3-}$eq)/kg COD); $E_{h,phosphate,ww,tn}$ considers the emissions from the wastewater of the anaerobic treatment system due to presence of total nitrogen (TN) in the POME (kg $PO_4^{3-}$eq); $TN_{h,ww,pome}$ is the amount of TN in the POME (kg TN); and $P_{o,tn}$ is the $PO_4^{3-}$ equivalence factor contributing to the EP impact due to TN (kg $PO_4^{3-}$eq/kg TN).

The life cycle impact assessment (LCIA) of the LCA is the phase in which the impact categories were assessed based on the midpoint impact categories using the methodology CML 2001. This phase is the most crucial in the overall LCA. The LCA involved calculating the environmental impact of POME-based electricity generation by the CLB and by the CSTR based on: global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP). GWP was assessed as the main aim of implementing biogas facilities in POMs is to mitigate greenhouse gas emissions, while AP is a type of impact that occurs as a result of changes in the base and acid equilibrium in water and in soil bodies due to the presence of contaminants such as $SO_2$, $NO_2$, NO and $NH_3$ [30,31]. The other environmental impact factor that was evaluated was EP. Eutrophication occurs due to the presence of very high micronutrient levels in the environment and causes excessive production of biomass [21]. In addition, to analyse the EP impacts of change in variations in the composition of sludge and amount of POME anaerobic sludge, a sensitivity analysis was conducted.

## 3. Results and discussion

### *3.1. Global warming potential with product displacement*

The GWP for the two different technologies was calculated based on the amount of input and the unit was expressed in kg $CO_2$ eq per kWh of electricity generated. Induced impact for each scenario is obtained by subtracting the avoided impacts from the induced impacts [32]. The GWP of the CLB system was -4.09 kg $CO_2$ eq per kWh of electricity generated and consisted of a mixture of displacement and emissions as follows: -4.13 kg $CO_2$ eq captured in the CLB system, 0.01 kg $CO_2$ eq of methane losses during the open pond treatment (facultative pond) and electricity emissions of 0.03 kg $CO_2$ eq from the pumps and other processes. The GWP of the CSTR system was -4.48 kg $CO_2$ eq, composed of: -4.71 kg $CO_2$ eq from three digester tanks capturing the biogas in the system; 0.08 kg $CO_2$ eq due to methane losses during the open pond treatment; and 0.15 kg $CO_2$ eq from emissions from electricity utilisation during the process. The results for both systems are illustrated in Fig. 1.

Even though both systems use a similar process (AD) for 1 kWh of energy generation, the GWP varies based on the input and output value of COD of POME. Based on the comparison of the GWP values for the two different treatment technologies, both technologies gave a negative GWP value, indicating a potential decrease in greenhouse gas emissions and a net decrease in $CO_2$ [22]. This is clearly shown by [33] where it was stated that the GWP reaches negative values because of the avoided $CO_2$ emissions as a result of energy conversion of the biomass. A decrease in the $CO_2$ value offset the other $CO_2$ emissions from the methane losses and electricity generated by both processes. It is also reported by [34] that the greenhouse gas emission reduction savings increase when the biogas produced from the methane captured is applied. However, the CSTR system seems to have a more negative GWP value compared to the CLB system. Moreover, the CSTR system is much more costly compared to the CLB system. Thus, the CLB system seems to be more cost-effective and the more attractive option. However, both technologies have great potential to create revenue from electricity generation [35].

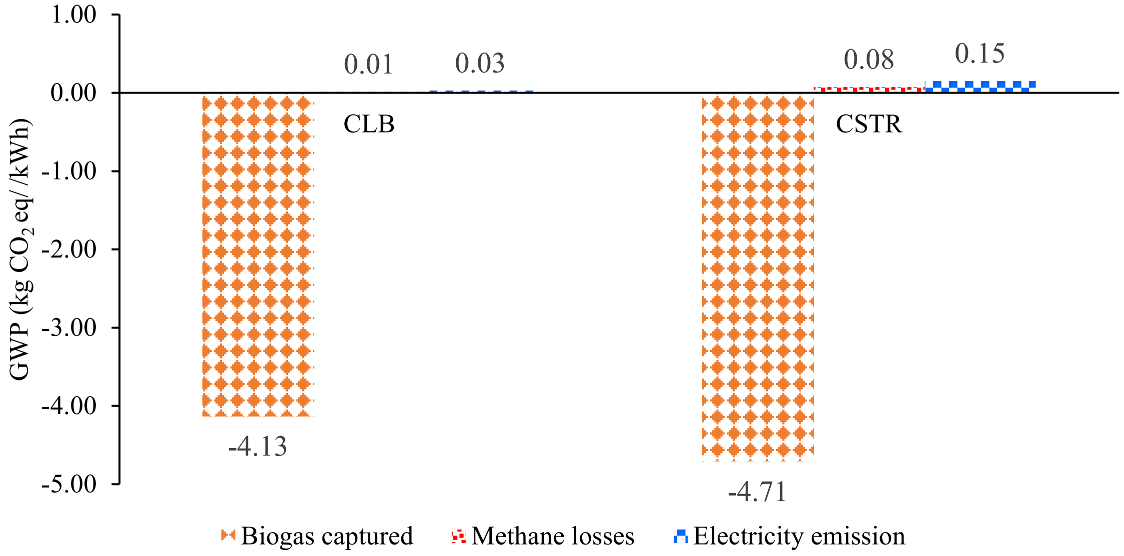


**Fig. 1.** GWP for CLB and CSTR systems

### 3.2. *Acidification potential with product displacement*

The CLB and CSTR systems both showed a negative value for AP, but the only contributor to this impact was $SO_2$ which was from the $H_2S$ composition of the biogas. The AP value for the CLB system was -0.15 kg $SO_2$ eq while for the CSTR system it was -2.21 kg $SO_2$ eq (Fig. 2).

As both systems are closed systems, it can be assumed that there are no $SO_2$ emissions. Also, [36] show that the presence of a biogas system produces a negative result for acidification potential, which equates to a net environmental benefit. Their analysis compared biogas and dung combustion in household cooking systems in developing countries. No diesel consumption is involved in the process, which further helps it to be more environmentally friendly. However, we found that the CSTR system has a greater negative value compared to the CLB system because the amount of POME used to generate 1 kWh of energy differs under each scenario. The hydrogen sulphide content in the CSTR system was higher than in the CLB system, resulting in a greater amount of sulphur dioxide being captured in the CSTR.

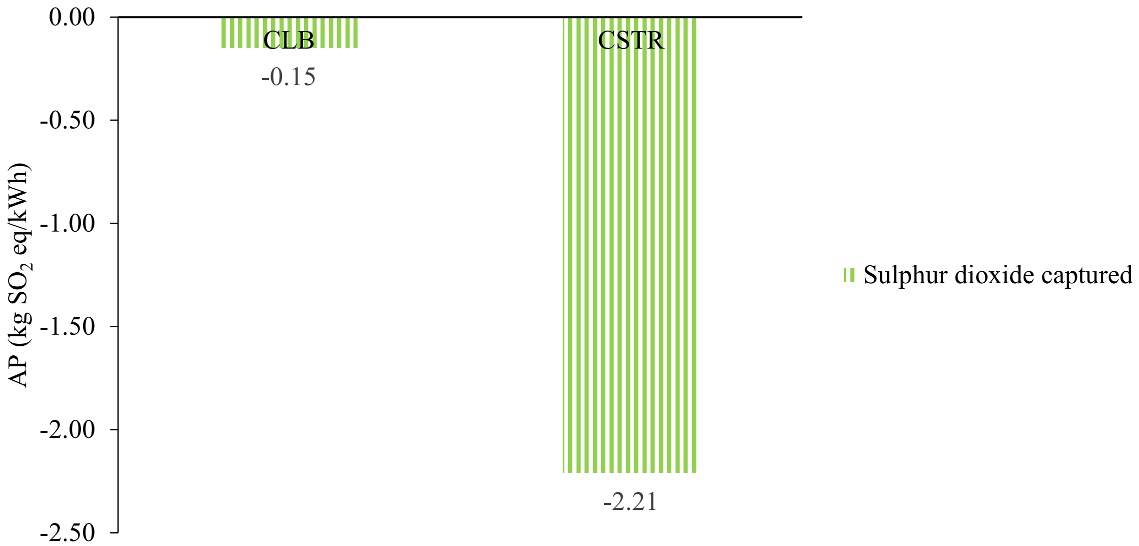


**Fig. 2.** AP for CLB and CSTR

### 3.3. *Eutrophication potential*

The other environmental impact factor that was evaluated was EP. In this study, the only biomass considered is POME; EFBs and FFBs are not taken into account. According to [19], the EP of POME is calculated based on the total phosphorus and nitrogen as well as the

COD mass fractions. However, in this study, the total phosphorus value of POME was not taken into account as it was not detected when the POME samples from every process were tested.

Fig. 3 provides the EP results for both systems. The CLB system and the CSTR system emitted 0.054 kg $PO_4^{3-}$eq and 0.048 kg $PO_4^{3-}$eq, respectively. The CLB system had a higher EP result in terms of emissions of $PO_4^{3-}$due to the absence of concrete in the pond wall before and after the AD system, which resulted in the POME dissolving in nearby land and water. Similarly, [22] reported the highest EP value for open lagoon technology due to the absence of concrete pond walls. However, the CLB system has a higher EP impact compared to the CSTR system because of the difference in amount of the POME used to generate 1 kWh of electricity.

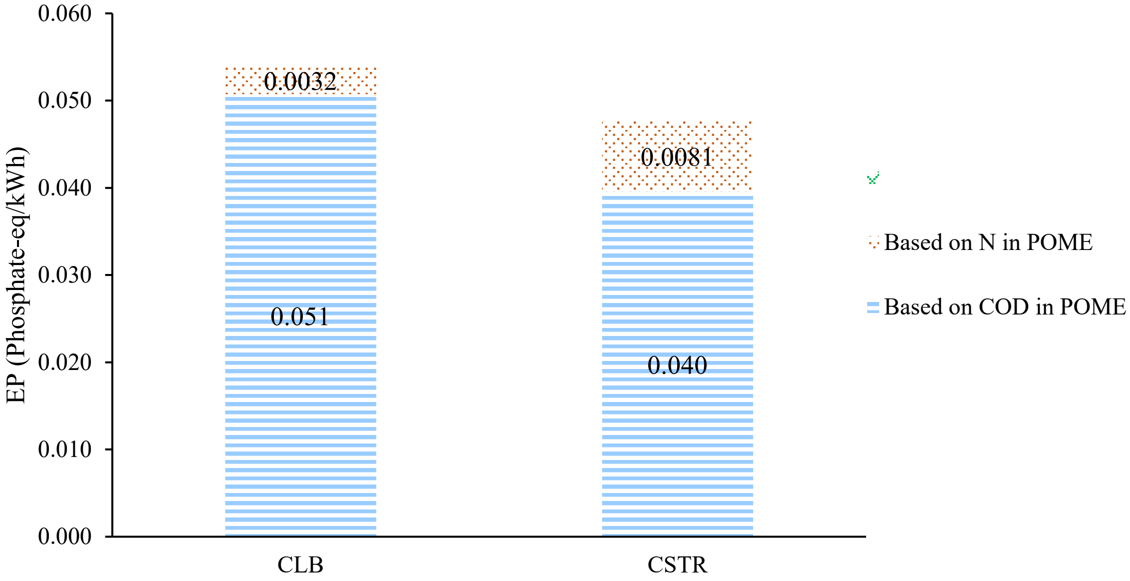


**Fig. 3.** EP for CLB and CSTR

The percentage relative contribution of the two different POME treatment technologies to the environmental impacts GWP, AP and EP is illustrated in Fig. 4. The preferred order of ranking of the two technologies is presented in Table 3. Both systems produced an overall negative value for GWP and AP, which represents a net environmental benefit. However, the CSTR system captured more $CO_2$ and $SO_2$, resulting in a higher negative percentage and better outcome compared to the CLB system. As for EP, both systems had a positive EP value and hence a negative impact on the environment. This is because the presence of COD and TN in POME tends to cause an EP impact due to the absence of concrete material in the pond wall, resulting in nitrification of land and water by both systems. However, the CSTR had a lower EP value than the CLB.

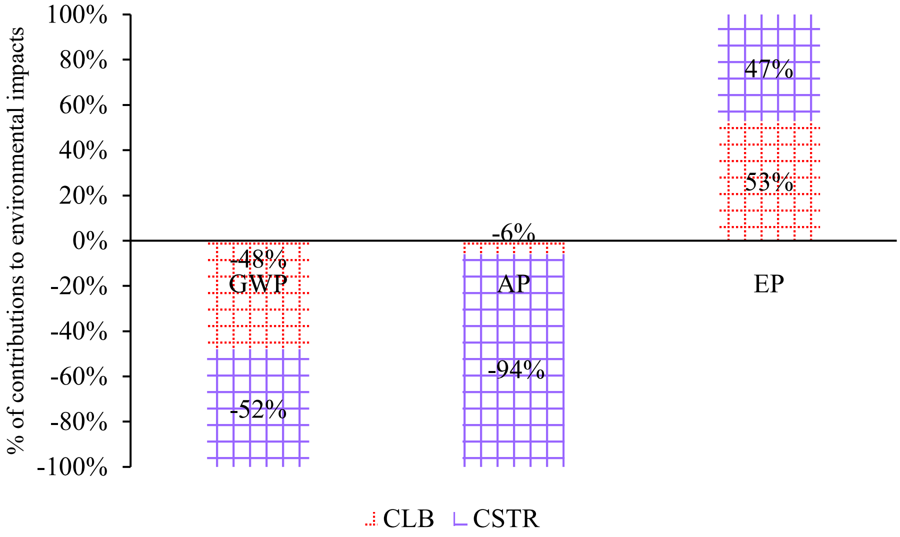


**Fig. 4.** Comparison of environmental impacts for CLB and CSTR

**Table 3** Preferred ranking of technologies for each environmental impact category

| Environmental impact category | Preferred ranking order |
|---|---|
| GWP with product displacement | CSTR > CLB |
| AP with product displacement | CSTR > CLB |
| EP | CSTR > CLB |

### *3.4. Sensitivity analysis*

Palm oil mills not only generate POME, a type of polluted wastewater; they also produce a large amount of POME sludge. POME sludge has great potential for use as an organic fertilizer [37] or compost. The most common type of POME sludge used for composting is POME anaerobic sludge, which is derived from the effluent of the AD digester. Sludge is also produced by the open treatment ponds or aerobic treatment [37], and is known as treated POME sludge. POME anaerobic sludge contains a high level of nutrients compared to treated POME sludge (Table 4). Both the CSTR and CLB systems produce a great amount of sludge as a result of treating POME for energy generation. Both systems produce 1.667 kg of sludge for 1 kWh of energy generation. Information was insufficiently available from the POMs on the properties of POME anaerobic and treated POME sludge, so the properties summarised in Table 4 were obtained from the literature.

**Table 4** Properties of POME anaerobic sludge and treated POME sludge

| Property | POME anaerobic sludge (A) [38] | Treated POME sludge (B) [37] |
|---|---|---|
| pH value | 7.41 | 7.40 |
| Moisture content (%) | 95.0 | 68.46 |
| Carbon (%) | 37.5 | 25.53 |
| Nitrogen (%) | 4.7 | 4.21 |
| C/N ratio | 6.7 | 6.35 |
| Volatile solids (%) | - | 89.43 |
| Total solids (%) | - | 32.40 |
| Phosphorus (%) | 1.25 ± 0.10 | 0.08 ± 0.01 |
| Potassium (%) | 5.16 ± 2.20 | 0.03 ± 0.01 |

In this study, EP has a negative environmental impact compared to GWP and AP in the case of both the CLB and CSTR systems. The total EP values for the CLB and CSTR systems were 0.054 kg $PO_4^{3-}$eq and 0.048 kg $PO_4^{3-}$eq, respectively. However, the total EP value of both systems can be offset by the application of 1.6667 kg sludge for composting for every 1 kWh of electricity generation. Currently, both POM 1 and POM 2 use POME anaerobic sludge for composting. In order to evaluate the use of sludge for composting as a possible solution to the EP impact, a sensitivity analysis was carried out, the results of which are illustrated in Fig. 5 and Fig. 6.

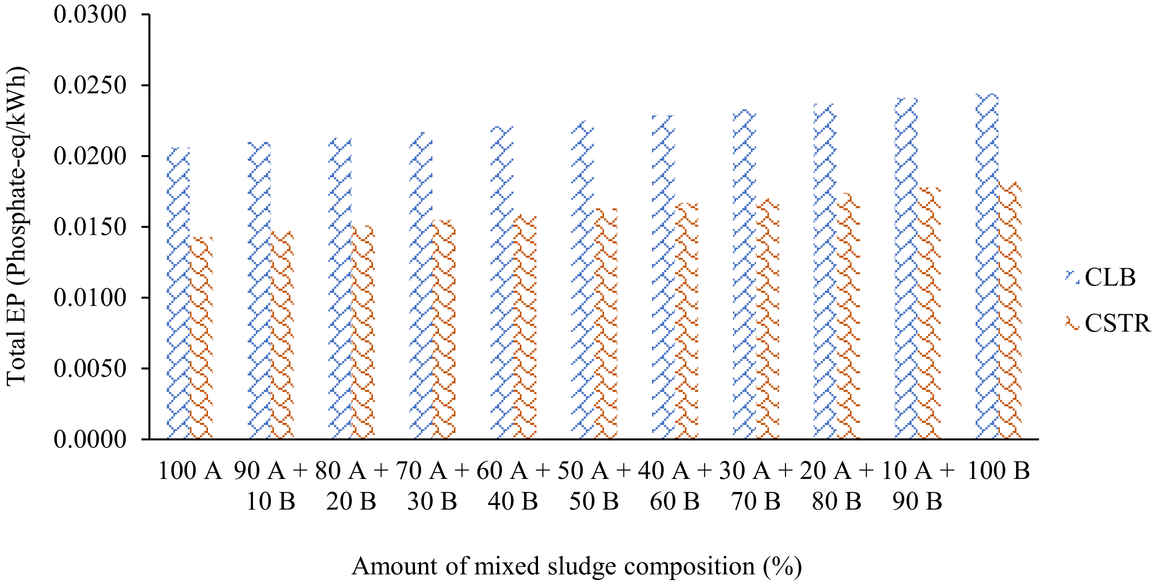


**Fig. 5.** Total EP impact based on variation in composition of sludge

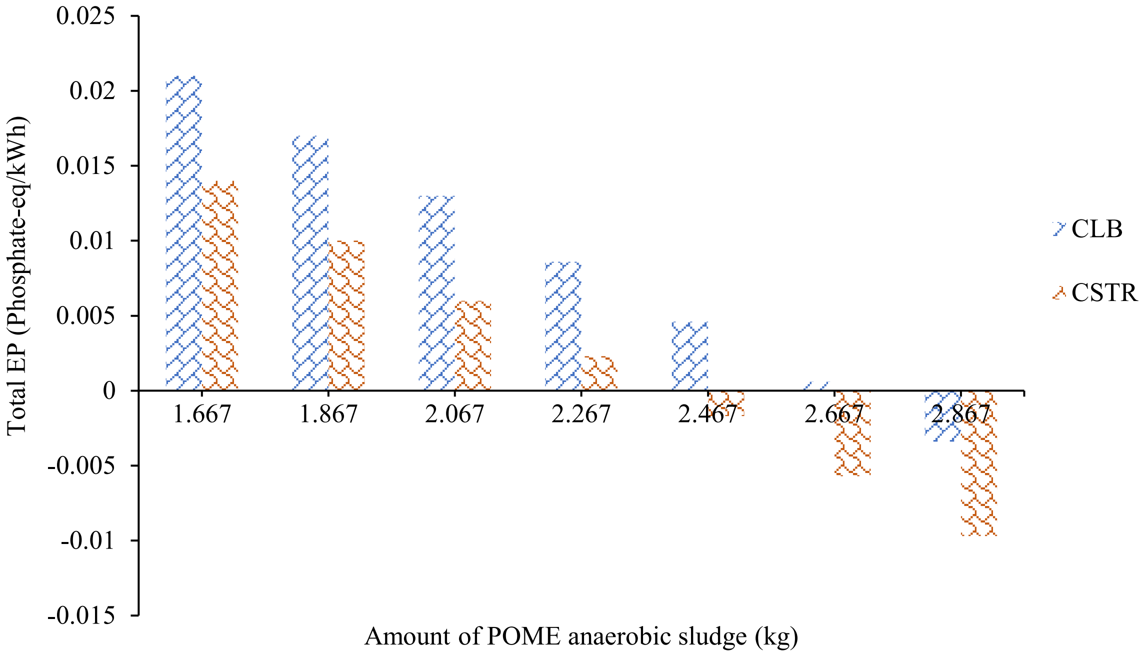


**Fig. 6.** Total EP impact based on variation in amount of POME anaerobic sludge

Fig. 5 shows that the total EP value gradually increases when the proportion of treated POME sludge in the mixed sludge increases in relation to the amount of POME anaerobic sludge. The lowest EP value is observed when the sludge is composed solely of POME anaerobic sludge. However, as shown in Fig. 6, the result differs markedly when only POME anaerobic sludge is used for composting. When the amount of POME anaerobic sludge is increased by approximately 0.2 kg, the total EP value reduces for the CLB and CSTR systems by 19% and 28.6%, respectively. This is due to the increment in the nitrogen and phosphorus content of this sludge, which contributes toward offsetting the overall EP impact.

The above results indicate that the EP value can only be improved by adding more POME anaerobic sludge. Altering the composition of 1.6667 kg of sludge that consists of POME anaerobic sludge and treated POME sludge by adding more treated POME sludge tends to increase the overall EP value (Fig. 5). This is because the amount of nitrogen and phosphorus in the mixture tends to reduce when more treated POME sludge is added, increasing the overall contribution of phosphate to the EP impact.

As the amount of POME anaerobic sludge used for composting increases, the total EP value tends to gradually decrease. The EP value drops below zero for the CSTR system when the amount of sludge used is 2.467 kg for 1 kWh of electricity generation. However, the EP value of the CLB system only drops below zero when the amount of sludge used is 2.867 kg for 1 kWh of electricity generation. This indicates that an increment of 1.2 kg of POME anaerobic sludge per 1 kWh could completely offset the total EP value for both CLB and CSTR systems, reducing the impact to below zero. Increasing the use of this type of sludge for composting would therefore result in a net environmental benefit, and building a concrete wall around the pond for both the CLB and CSTR systems would definitely improve the EP result even further.

## 4. Conclusion

The aim of this study was to undertake a LCA of two different POME treatment technologies in two POMs in order to identify whether employing a closed AD system would be more beneficial from an environmental perspective. Our key findings show that:

- Both the CLB and CSTR systems have a net environmental benefit in terms of GWP and AP. However, the CSTR system captured 0.39 kg $CO_2$ eq/kWh and 2.06 kg $SO_2$ eq/kWh more than the CLB system.
- In terms of the EP impact, the CSTR system was more beneficial as it emitted 0.006 kg $PO_4^{3-}$eq less than the CLB system. Mitigation measures, such as the use of concrete for the pond wall, are crucial to reduce the EP impact of both systems. Moreover, increasing the amount of anaerobic POME sludge used for composting by 1.2 kg per 1 kWh can result in an EP value below zero.

The findings presented offer important insights to encourage mill owners to implement more environmentally friendly biogas facilities in POMs. Such facilities could generate energy and increase the contribution of biogas to the primary energy production mix in Malaysia. Malaysia has committed to reducing GHG emissions by 45% by 2030 in its Nationally Determined Contributions under the Paris Agreement. As such, finding ways in which to increase the share of renewables in the national energy mix, while also dealing with POME waste, is both nationally and globally important.

Issues to be addressed in future research are varied. A wider range of boundaries should be focussed on where possible, as this study only looked at gate to gate considerations due to data limitations. Further research is needed to study the impacts of the final discharge. For instance, impacts from digestate POME following land application should be taken into consideration. Additionally, collection of primary data on the properties of POME anaerobic sludge is needed to further verify the results of the sensitivity analysis. LCA can be conducted using different methodologies to those used here, such as ReCiPe, which looks into endpoint impacts, including those on the end user of the electricity generated by the national grid. A wider range of POME treatment to energy generation technologies from other countries could be compared for a more comprehensive picture of options. Our study considered two different treatment technologies due to its focus on systems in Malaysia, where application of different types of POME treatment to energy generation technologies is currently limited.

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## References

[1] MPOB. Malaysian oil palm statistics 2017. 37th ed. Bangi,Malaysia: Malaysian Palm Oil Board;2018. p. 205.

[2] Kushairi A, Kheang LS, Azman I, Hishamuddin E, Ong-Abdullah M, Izuddin ZBMN, et al. Oil palm economic performance in Malaysia and r&d progress in 2017. J Oil Palm Res 2018;30(2):163-95.

[3] Yasin MHM, Mamat R, Najafi G, Ali OM, Yusop AF, Ali MH. Potentials of palm oil as new feedstock oil for a global alternative fuel: A review. Renew Sust Energ Rev 2017;79:1034–49.

[4] Sue TT, Pantzaris TP. Chapter 6-energy from oil palm biomass. Pocketbook of oil palm uses. Malaysia: Malaysian Palm Oil Board;2017. p. 139.

[5] Abdulrazik A, Elsholkami M, Elkamel A, Simon L. Multi-products productions from Malaysian oil palm empty fruit bunch (EFB): Analyzing economic potentials from the optimal biomass supply chain. J Clean Prod 2017;168:131–48.

[6] Loh SK. The potential of the Malaysian oil palm biomass as a renewable energy source. Energ Convers Manage 2017;141:285–98.

[7] Saelor S, Kongjan P, O-Thong S. Biogas production from anaerobic co-digestion of palm oil mill effluent and empty fruit bunches. In: The international conference on “alternative energy in developing countries and emerging economies”;2017. p. 717-22 [Bangkok, Thailand].

[8] Kamyab H, Chelliapan S, Din MFM, Rezania S, Khademi T, Kumar A. Chapter 2-palm oil mill effluent as an environmental pollutant. Palm oil. Malaysia: IntechOpen;2018. p. 13-28.

[9] Choong YY, Chou KW, Norli I. Strategies for improving biogas production of palm oil mill effluent (POME) anaerobic digestion: A critical review. Renew Sust Energ Rev 2018;82:2993-3006.

[10] Li Y, Chen Y, Wu J. Enhancement of methane production in anaerobic digestion: A review. Appl Energ 2019;240:120-37.

[11] Safari GH, Yetilmezsoy K, Mahvi AH, Zarrabi M. Post-treatment of secondary wastewater treatment plant effluent using a two-stage fluidized bed bioreactor system. J Environ Health Sci 2013;11(10):1-9.

[12] Ahmed Y, Yaakob Z, Akhtar P, Sopian K. Production of biogas and performance evaluation of existing treatment processes in palm oil mill effluent (POME). Renew Sust Energ Rev 2015;42:1260–78.

[13] Daud MK, Rizvi H, Akram MA, Ali S, Rizwan M, Nafees M, et al. Review of upflow anaerobic sludge blanket reactor technology: Effect of different parameters and developments for domestic wastewater treatment. J Chem-Ny 2018;1–13.

[14] Emadian SM, Rahimnejad M, Hosseini M, Khoshandam B. Investigation on upflow anaerobic sludge-fixed film (UASFF) reactor for treating low-strength bilge water of caspian sea ships. J Environ Health Sci Eng 2015;13(23):1-9.

[15] Zhu G, Jha AK. Psychrophilic dry anaerobic digestion of cow dung for methane production: Effect of inoculum. Science Asia 2013;39:500-10.

[16] Cruz-Salmon A, Rios-Valdovinos E, Pola-Albores F, Lagunas-Rivera S, Meza-Gordillo R, Ruiz-Valdiviezo VM, et al. Expanded granular sludge bed bioreactor in wastewater treatment. J Environ Sci Manage 2019;5(1):119–38.

[17] Mutungwazi A, Mukumba P, Makaka G. Biogas digester types installed in South Africa: A review. Int J Hydrogen Energ 2018;81:172-80.

[18] Kariyama ID, Zhai X, Wu B. Influence of mixing on anaerobic digestion efficiency in stirred tank digesters: A review. Water Res 2018;143:503-17.

[19] Carneiro MLNM, Pradelle F, Braga SL, Gomes MSP, Martins ARFA, Turkovics F, et al. Potential of biofuels from algae: Comparison with fossil fuels, ethanol and biodiesel in Europe and Brazil through life cycle assessment (LCA). Renew Sust Energ Rev 2017;73:632–53.

[20] Stichnothe H, Schuchardt F. Comparison of different treatment options for palm oil production waste on a life cycle basis. Int J Life Cycle Ass 2010;15:907–15.

[21] Garcia-Nunez JA, Rodriguez DT, Fontanilla CA, Ramirez NE, Silva Lora EE, Frear C S, et al. Evaluation of alternatives for the evolution of palm oil mills into biorefineries. Biomass Bioenerg 2016;95:310–29.

[22] Nasution MA, Wibawa SD, Ahamed T, Noguchi R. Comparative environmental impact evaluation of palm oil mill effluent treatment using a life cycle assessment approach: A case study based on composting and a combination for biogas technologies in North Sumatera of Indonesia. J Clean Prod 2018;184:1028–40.

[23] Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K. IPCC Guidelines for National Greenhouse Gas Inventories. Hayama, Japan: Institute for Global Environmental Strategies;2006(a).

[24] CDM. Study on Grid Connected Electricity Baselines in Malaysia. Malaysia: Clean Development Mechanism;2014.

[25] Doorn MRJ, Towprayoon S, Vieira SMM, Irving W, Palmer C, Pipatti R, et al. Chapter 6-wastewater treatment and discharge. IPCC Guidelines for National Greenhouse Gas Inventories. Hayama, Japan: Institute for Global Environmental Strategies;2006(b).

[26] Lim XL, Lam WH. Review on clean development mechanism (CDM) implementation in Malaysia. Renew Sust Energ Rev 2014;29:276-85.

[27] CDM. CDM project 2336: Felda Serting Hilir biogas power plant project. Malaysia: Clean Development Mechanism, http://cdm.unfccc.int/Projects/DB/SGS-UKL1227808382.8/view;2008 [accessed 10 February 2019].

[28] Eshun JF, Apori SO, Oppong-Anane K. Environmental system analysis of tomato production in Ghana. Afr. Crop Sci. J. 2011;19(3):165–72.

[29] UNFCC. CDM Methodology Booklet. Bonn, Germany: United Nations Framework Convention on Climate Change, https://cdm.unfccc.int/methodologies/documentation/meth_booklet.pdf;2017 [accessed 6 February 2019].

[30] Chan YH, Tan RR, Yusup S, Lam HL, Quitain AT. Comparative life cycle assessment (LCA) of bio-oil production from fast pyrolysis and hydrothermal liquefaction of oil palm empty fruit bunch (EFB). Clean Techn Environ Policy 2016;18:1759–68.

[31] Chatterjee R, Sharma V, Mukherjee S, Kumar S. Life cycle assessment of bio-diesel production – a comparative analysis. J. Inst. Eng. India Ser. C 2014;95(2):143–49.

[32] Woon KS, M.C Lo I, L.H. Chiu S, Y.S Yan D. Environmental assessment of food waste valorization in producing biogas for various types of energy use based on LCA approach. Waste Manage 2016;50:290-9.

[33] Lorenzi G, Gorgoroni M, Silva C, Santarelli M. Life Cycle Assessment of biogas upgrading routes. In: The 10th international conference on “applied energy”;2018. p. 2012-18 [Hong Kong, China].

[34] Harsono SS, Grundmann P, Siahaan D. Role of biogas and biochar palm oil residues for reduction of greenhouse gas emissions in the biodiesel production. In: The 3rd international conference on “new, renewable energy and energy conservation”;2015. p. 344-51 [Jakarta, Indonesia].

[35] Nasution MA, Wibawa SD, Ahamed T, Noguchi R. Selection of palm oil mill effluent treatment for biogas generation or compost production using an analytical hierarchy process. J Mater Cycles Waste Manag 2017;1–13.

[36] Lansche J, Muller J. Life cycle assessment (LCA) of biogas versus dung combustion household cooking systems in developing countries: A case study in Ethiopia. J Clean Prod 2017;165:828-35.

[37] Khairuddin MdN, Zakaria AJ, Isa IMd, Jol H, Wan-Mohd-Nazri WAR, Salleh MdKS. The potential of treated palm oil mill effluent (pome) sludge as an organic fertilizer. AGRIVITA J Agr Sci 2016;38(2):142-54.

[38] Baharuddin AS, Hock LS, Yusof MZM, Rahman NAB, Shah UkM, Hassan MA, et al. Effects of palm oil mill effluent (POME) anaerobic sludge from 500 $m^3$ of closed anaerobic methane digested tank on pressed-shredded empty fruit bunch (EFB) composting process. Afr J Biotechnol 2010;9(16):2427-36.