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EVALUATION OF POME-BIOGAS PRODUCTION SYSTEM FOR ECO-EFFICIENCY IMPROVEMENT IN SELECTED PALM OIL MILLS IN MALAYSIA

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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The release of massive amount of methane gas into the atmosphere from the POME treatment ponds has made many realize that the industry must be sustainable if its national and international market is to be safeguarded. Malaysian palm oil mills have been encouraged to implement biogas facilities in the mills to capture the methane gas and used it for power generation. However, different configurations of biogas capture technology and biogas utilization pathway currently adopted in palm oil mills may lead to a great variance of outcomes from both environmental and economic point of views. This situation could subsequently affect the selection and decision on an appropriate AD system among the palm oil industry players. Therefore, the objectives of this study are 1) to determine the environmental impacts and costs incurred for eco-environmental conservation of Malaysian palm oil mills with different POME-biogas systems using Life Cycle Assessment (LCA) and Environmental Life Cycle Costing (ELCC) approach, 2) to evaluate the environmental and economic performance of Malaysian palm oil mills with current POME-biogas production systems, and 3) to develop an improvement assessment model for a better decision making among the palm oil industry players using Eco-costs Value Ratio (EVR) model.

From the environmental perspective, 11 impact categories have been determined in palm oil mills using Eco-indicator 99 methodology embedded in an LCA software called SimaPro Version 8.0. Based on the weighted results, respiratory inorganics, climate change and fossil fuels depletion are identified as the most significant impact categories. The impacts that contributed to the first two impact categories are primary derived from the application of chemical fertilizers in plantations and highly dependent on diesel for transportation and machinery both in plantations and palm oil milling processes. As for the fossil fuels depletion impact category, the contributing units to this are believed to be derived from the activities of chemical fertilizers

production and transporting of the manufactured fertilizers and fresh fruit bunches (FFBs) from plantation to mill.

Meanwhile, the total costs incurred in the palm oil mills with different POME-biogas production systems include fixed costs, depreciation costs and variable costs have been determined and computed. Amongst, production costs for CPO and kernel are identified as the most significant cost components in the capital budgeting analysis. This is believed to be attributed to the low FFB processed and high milling cost. Net present value (NPV), internal rate of return (IRR), benefit cost ratio (BCR) and payback period (PBP) of a financial projection of different biogas systems have been analyzed. The results have revealed that the biogas configuration with AD tank to grid connection system is more financially viable; greater profitability with shorter payback period. Besides, it is also found that the financial projection of each biogas configuration is identically sensitive when the quantity of crude palm oil (CPO) production is decreased, instead of the increment of biogas investment. It is believed that the sustainable supply of FFB from plantations and consistency production of CPO in the mill has a dominant effect on its financial viability.

From the eco-efficiency analysis perspective, the results have revealed that palm oil mill with biogas configuration of AD tank to grid connection system has the lowest eco-costs value ratio (EVR) value among the groups; 0.08. Whereas, palm oil mill with biogas configuration of AD tank to co-firing system has showed to have the highest EVR value; 0.31. This also indicated that palm oil mill with biogas configuration of AD tank to grid connection has the highest eco-efficiency and it can be said that it is the most sustainable palm oil mill in terms of environmental and economic aspects. In fact, all palm oil mills are found to be eco-efficiency from environmental and economic point of views due to their low EVR values. Eco-efficiency of all palm oil mills would improve when the green procurements in plantations are taken seriously and the milling technological is revolutionized with advanced technologies. In a nutshell, this finding has proved that Malaysian palm oil mills with biogas facilities are indeed sustainable from environmental and economic aspects. It is also suggested that the adoption of biogas configuration of AD tank to grid connection would lead a positive effect to the palm oil industry in terms of a long run environmental protection and safeguard of economic.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENILAIAN SISTEM PENGHASILAN POME-BIOGAS BAGI PENAMBAHBAIKAN EKO KECEKAPAN DI KILANG KELAPA SAWIT TERPILIH, MALAYSIA

Oleh

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Pembebasan gas metana yang berkuantiti besar ke atmosfera dari kolam rawatan POME telah menyebabkan banyak pihak menyedari bahawa kemampanan di industri minyak sawit perlu dicapai jika pasaran kebangsaan dan antarabangsa ingin dijamin. Kilang minyak kelapa sawit Malaysia telah digalakkan untuk melaksanakan kemudahan biogas di kilang untuk menangkap gas metana dan menggunakannya untuk penjanaan kuasa. Walaubagaimanapun, konfigurasi yang berlainan dari segi teknologi penangkapan biogas dan laluan pemanfaatan biogas yang sedang digunakan di kilang kelapa sawit boleh menyebabkan variasi hasil yang besar dari kedua-dua sudut pandangan alam sekitar dan ekonomi. Keadaan ini boleh menjejaskan pemilihan dan keputusan pada sistem AD yang sesuai dalam kalangan pihak industri minyak sawit. Oleh itu, objektif kajian ini adalah untuk 1) mengenal pasti impak-impak alam sekitar dan kos yang timbul untuk pemuliharaan eko-alam sekitar di kilang kelapa sawit Malaysia yang mempunyai sistem POME-biogas yang berbeza dengan menggunakan pendekatan Penilaian Kitaran Hayat (LCA) dan Kos Kitaran Hayat Alam Sekitar (ELCC), 2) menilai prestasi alam sekitar dan ekonomi kilang minyak sawit Malaysia yang ada sistem pengeluaran POME-biogas yang berbeza, dan 3) mewujudkan model penilaian penambahbaikan untuk membuat keputusan yang lebih sesuai dalam kalangan pihak industri minyak sawit.

Dari perspektif alam sekitar, sebanyak 11 kategori impak telah ditentukan di kilang kelapa sawit menggunakan metodologi Eco-indicator 99 yang terdapat dalam perisian LCA yang dikenali sebagai SimaPro Versi 8.0. Berdasarkan kepada keputusan wajaran, inorganik pernafasan, perubahan iklim dan pengurangan bahan api fosil telah dikenalpasti sebagai kategori impak yang paling ketara. Kesan yang menyumbang kepada dua kategori impak pertama adalah akibat daripada penggunaan baja kimia di ladang dan penggunaan diesel untuk akitiviti pengangkutan di ladang dan jentera

semasa proses penghasilan minyak kelapa sawit di kilang. Bagi kategori impak bahan api fosil yang berkurangan, unit yang menyumbang kepada impak ini adalah dipercayai diperolehi daripada aktiviti penghasilan baja kimia dan pengangkutan baja kimia tersebut dari ladang ke kilang.

Di samping itu, jumlah kos yang diperlukan untuk pemprosesan minyak kelapa sawit dengan sistem penghasilan POME-biogas yang berbeza di kilang kelapa sawit termasuk kos tetap, kos susut nilai dan kos berubah telah dikenalpasti dan dihitung. Di antaranya, kos pengeluaran untuk CPO dan kernel telah dikenalpasti sebagai komponen kos yang paling ketara dalam analisis belanjawan modal. Hal ini dipercayai berlaku kerana FFB yang diproses di kilang adalah rendah dan kos penggilingan yang tinggi. Nilai semasa bersih (NPV), kadar pulangan dalaman (IRR), nisbah kos manfaat (BCR) dan tempoh bayaran balik (PBP) dalam unjuran kewangan sistem biogas yang berbeza juga telah dianalisis. Hasilnya menunjukkan bahawa konfigurasi biogas dengan tangki AD ke sistem sambungan grid mempunyayi keuntungan yang lebih tinggi dan tempoh pemulihan kos pelaburan yang singkat. Di samping itu, unjuran kewangan bagi setiap konfigurasi biogas adalah sesama sensitif apabila jumlah pengeluaran minyak sawit mentah (CPO) menurun berbanding dengan kenaikan kos pelaburan biogas. Oleh itu, bekalan FFB yang mampan daripada perladangan dan pengeluaran CPO yang berkonsisten di kilang dipercayai mempunyai kesan dominan terhadap daya maju kewangannya.

Dari perspektif analisis eko kecekapan, hasilnya menunjukkan bahawa kilang minyak kelapa sawit dengan konfigurasi biogas tangki AD ke sistem sambungan grid mempunyai nilai nisbah eko-kos dengan kos (EVR) yang terendah dalam kalangan kumpulan kilang sawit yang dinilai; 0.08. Manakala, kilang kelapa sawit dengan konfigurasi biogas tangki AD dengan sistem penembakan mempunyai nilai EVR yang tertinggi; 0.31. Ini juga menunjukkan bahawa kilang kelapa sawit dengan konfigurasi biogas tangki AD ke sambungan grid mempunyai eko kecekapan yang tertinggi dan ia juga boleh dikenali sebagai kilang sawit yang paling mampan dari segi aspek alam sekitar dan ekonomi. Sebenarnya, semua kilang sawit yang dinilai di kajian ini didapati mencapai eko kecekapan dari sudut pandangan alam sekitar dan ekonomi kerana nilai EVR mereka adalah rendah. Eko kecekapan semua kilang sawit dipercayai akan bertambah baik apabila perolehan akitiviti hijau di ladang diambiltindak dengan serius dan teknologi pengilangan merevolusikan dengan teknologi maju. Ringkasannya, penemuan dari kajian ini membuktikan bahawa kilang kelapa sawit Malaysia dengan kemudahan biogas adalah lestari dari aspek alam sekitar dan ekonomi. Penemuan ini juga mencadangkan bahawa penggunaan konfigurasi biogas tangki AD ke sambungan grid akan membawa kesan positif kepada industri minyak sawit untuk perlindungan alam sekitar dan ekonomi dari segi jangka masa panjang.

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LIST OF ABBREVIATIONS

ABC	Activity-based Costing
AD	Anaerobic Digestion
ASEAN	Association of South East Asian Nations
BCR	Benefit Cost Ratio
BOD	Biochemical Oxygen Demand
CAPEX	Capital Expenditure
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CF	Cash flow
CH_4	Methane
CHP	Combined Heat and Power
CNG CO_2-eq	Carbon dioxide equivalent
COD	Chemical Oxygen Demand
CSTR	Continuous Flow Stirred Tank Reactor
CPKO	Crude Palm Kernel Oil
CPO	Crude Palm Oil
CV	Calorific Value
DALY	Disability Adjusted Life Years
DOE	Department of Environment
EC	European Commission
ECCAPEX	Energy Commission
EEA	Energy Efficiency Analysis
EFB	Empty Fruit Bunch
EGSB	Expanded Granular Sludge Bed
ELCC	Environmental Life Cycle Costing
EIA	Environmental Impact Assessment
EMS	Environmental Management System
EIA	Environmental Protection Agency (US)
EPPs	Entry Eight Projects
EPU	Economic Planning Unit
EU	European Union
EVR	Eco-cost Value Ratio

FFB	Fresh Fruit Bunch
FELCRA	Federal Land Consolidation and Rehabilitation Authority
FELDA	Federal Land Development Authority
FFA	Free Fatty Acids
FiT	Feed-in Tariff
FU	Functional Unit
GDP	Gross Domestic Product
GEF	Global Environment Facility
GHG	Greenhouse Gas
GNI	Gross National Income
GWP	Global Warming Potential
H_2S	Hydrogen Sulfide
H_2SO_4	Sulphuric Acid
HDPE	High Density Polyethylene Membrane
HRT	Hydraulic Retention Time
ILCD	International Reference Life Cycle Data System
IRR	Internal Rate of Return
KeTTHA	Ministry of Energy, Green Technology and Water (Kementerian Tenaga, Teknologi Hijau dan Air)
ktoe	Kilotonne of oil equivalent
IMP3	Third Industrial Master Plan
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISO	International Standard Organization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LLDPE	Linear Low Density Polyethylene
LNG	Liquefied Natural Gas
MEIH	Malaysia Energy Information Hub
MJ	Megajoule
MIRR	Modified Internal Rate of Return
MPOB	Malaysian Palm Oil Board

MPOC	Malaysian Palm Oil Council
MSPO	Malaysian Sustainable Palm Oil
MSW	Municipal Solid Waste
MT or ton	Metric tonne or tonne
MW	Megawatt
MY-LCID	Malaysia Life Cycle Inventory Database
NER	Net Energy Ratio
NGO	Non-governmental Organization
NH_3	Ammonia
$NH_4 – N$	Ammoniacal-nitrogen
NKEA	National Key Economic Areas
NO_x	Nitrogen Oxides
NPV	Net Present Value
NRE	Natural Resources and Environment
NVA	Net Value Added
OPEX	Operational Expenditure
OPP3	Third Outline Perspective Plan
ORT	Organic Loading Rate
PBP	Payback Period
PDF	Potentially of Disappeared Fraction
PK	Palm Kernel
PME	Palm Oil Methyl Ester
POME	Palm Oil Mill Effluent
PORIM	Palm Oil Research Institute of Malaysia
PORLA	Palm Oil Registration and Licensing Authority
PSA	Pressure Swing Adsorption
PTM	Pusat Tenaga Malaysia/Malaysia Energy Centre
P&C	Private and Confidential
R&D	Research and Development
RE	Renewable Energy
RISDA	Rubber Industry Smallholder Development Authority
RM	Ringgit Malaysia
ROI	Return On Investment
RSPO	Roundtable on Sustainable Palm Oil

SA	Sensitivity Analysis
SEDA	Sustainable Energy Development Authority
SETAC	Society of Environmental Toxicology and Chemistry
SimaPro	System for Integrated environMental Assessment of PROducts
SIRIM	Standards and Industrial Research Institute of Malaysia
SO_2	Sulphur dioxide
SREP	Small Renewable Energy Power
SRP	Subsidy Rationalization Program
TS	Total Solid
TSS	Total Suspended Solid
UN	United Nations
UNDP	United Nation Development Program
UNFCCC	United Nations Framework Convention on Climate Change
UASB	Up-flow Anaerobic Sludge Blanket
US	United States
USEPA	United States Environmental Protection Agency
VA	Value Added
VFA	Volatile Fatty Acid
8-MP	Eighth Malaysian Plan
9-MP	Ninth Malaysian Plan
10-MP	Tenth Malaysian Plan
11-MP	Eleventh Malaysian Plan

CHAPTER 1

INTRODUCTION

1.1 Introduction

Global warming has become one of the prominent global issues and its impacts towards human health and environment have always captured the attention of people around the world. Global warming can be attributed to a substantially increase of fossil fuel combustion in which it subsequently leads to a great amount of greenhouse gases (GHG) to be emitted into the atmosphere. In addition to the rapid growth of population and urbanization facing in world, the GHG emission rate has become even higher as this significant global development would require a greater amount of energy for power generation. This situation can easily be seen in both the economies of the United States and China as the countries are more developed and therefore, they have been recognized as the world's first and second largest energy users, respectively (IEA, 2010). This would also imply that United States stands as the crux CO_2 emitter in the global arena followed by China. However, China has then quickly surplused United States in terms of CO_2 emissions in 2014 and becomes the world top CO_2 emitter (Table 1.1) (IEA, 2010; USEPA, 2017). Consequently, both of the countries have been pressured to take lead in tackling the concerned problem. Nevertheless, the impacts contributed by other GHG emitters that involved many more developed and developing countries inclusive of Malaysia should not be underrated.

According to IEA (2013), Malaysia has been reported to be the third largest energy consumer in ASEAN countries and it is anticipated that the per capita power consumption in the country will further escalate as the country becomes more developed. In fact, Malaysia has experienced a significant economic growth in the recent years. Undeniably, this situation has led the country to utilize more fossil -based energy especially natural gas (53%) and coal (39%) in powering most of the sectors in Malaysia. Ultimately, it will lead to a concomitant acceleration in GHG emissions. According to Natural Resources and Environment (NRE) (2011), it is also anticipated that the annual GHG emissions in Malaysia will increase by 74% by 2020 in comparison to the 2005 level, if the country continues to highly dependent on the fossil-based energy. From this point of view, Malaysia might become one of the world most prominent CO_2 emitters in the future if efforts in alleviating CO_2 emissions are not seriously undertaken, though the GHG emitted so far is considerably small compared to both China and the United States.

Table 1.1 : Global CO_2 emissions from fossil fuel combustion and industrial processes

Country	CO_2 emissions (%) in 2014
China	30
United States	15
European Union	9
India	7
Russian Federation	5
Japan	4
Other (inclusive of Malaysia)	30
Total	100

(Source: Modified from USEPA 2017 and Boden et al., 2017)

Since 1990, there was move to negotiation has commenced globally regarding the carbon emission issue and promises to reduce CO_2 into the atmosphere by maximizing renewable energy (RE) utilization (Global Carbon Project, 2014). However, this is merely a blatter rather than a promise as the global carbon emissions at the moment have increased to 65% compared to that in 1990 (Global Carbon Project, 2014). In the current trend of 370 billion tons of carbon emissions, it is predicted that it will hit 432 billion tons by 2019, of which 127 billion tons will be mostly contributed by China (Global Carbon Project, 2014). This rapid increment serves as a vital reminder and should have awakened all nations to start consciously playing their parts for deeper GHG cut. It is worth noted that everybody has responsibility when it comes to developing a low carbon economy for the society and the environment.

As aforementioned, utilization of RE can be identified as a feasible solution in mitigating carbon emissions and reducing fossil fuel dependency. In addition, in recent years, RE and sustainable energy (green technology) have also been recognized to play a significant driving force in improving country's economic status and diminishing the adverse impacts on the environment. As such, various regulations and incentives favoring RE and green technology have been rapidly formulated and put in force by the governments in many countries. As a result, more RE and green technology and efforts looking for alternative energy sources have been spearheaded in many universities, institutions and industries. This phenomenon is prevalent in Malaysia in the recent years. Of the various local RE sources, with the release of the National Renewable Energy Policy and Action Plan (2009) and Renewable Energy Act (2011), biomass resources and biogas from palm oil mill effluent (POME) has specifically been one of the most focused and concerned research subjects in the country's RE field.

1.2 Availability of POME and the need for POME treatment

The Malaysian palm oil industry is one of the biggest contributors to the national economy because it has reportedly contributed RM53 billion in the country's Gross National Income (GNI) and will increase to RM178 billion by 2020 (NKEA, 2013).

Hence, its activities are expected to further accelerate. In 1990, the oil palm planted area in Malaysia was only 2.03 million hectares. In 2015, the total oil palm planted area has expanded to 5.64 million hectares; private estates (61%), independent smallholders (16%), FELDA (13%), state agencies (6%), FELCRA (3%) and RISDA (1%) (MPOB, 2015). This indicates that the private sector has dominated the plantation industry and would be the main driver for rapid growth of palm oil production and development. At current stage, the industry is able to produce adequate oils not just for domestic consumption but also for export market which is accounted for 37% of world exports (MPOC, 2017). Currently, Malaysia is the world second largest palm oil producer and exporter after Indonesia. Although this expansion has significantly escalated the national economy; and it too has generated tremendous liquid wastewater i.e. palm oil mill effluent (POME) and other milling by-products; in times it will lead the industry to a serious by-products handling and management in palm oil mills associated with the fresh fruit bunch (FFB) processing. Nevertheless, these oil palm by-products are projected to contribute an approximately of RM6.379 billion of energy annually (Jaafar et al., 2003).

In the milling processes, a huge amount of water is required to extract crude palm oil (CPO) from FFB. Typically, the water for milling processes is sourced from the nearby rivers which require a lower pumping cost. From FFB, an approximate of 50% of the water used will end up becoming POME. As reported, the average rate of POME production from the Malaysian palm oil mills ranges from 0.67 to 0.75 m^3 for every ton of FFB processed (Ng et al., 2011; Ma, 1999). Other by-products generated in diversified form along with POME are empty fruit bunch (EFB), mesocarp fiber and shell which are accounted for 23%, 13% and 7%, respectively (Corley & Tinker, 2003; Sridhar & AdeOluwa, 2009; Loh, 2016). Of these, POME is the most abundant source of by-product in palm oil mills. POME is commonly known as an oily wastewater that is produced during palm fruits sterilization, palm oil clarification and hydro cyclone process (Borja et al., 1996a; Wu et al., 2010; Liew et al., 2015). It is a non-toxic organic waste because no chemical is added during oil extraction (Igwe & Onyegbado, 2007). It is high in biochemical oxygen demand (BOD) (25,000 mg/L), chemical oxygen demand (COD) (50,000 mg/L), and solids concentration (40,500 mg/L) with acidity around pH 3.8-4.5 (Yacob et al., 2006a; Ma et al., 1993; Poh et al., 2010; Rupani et al., 2010) and therefore can be a good nutrient source for microorganisms' growth. Consequently, it is a highly suitable feedstock in anaerobic digestion (AD) which naturally produces biogas and is released to the atmosphere. However, POME could be a serious threat to the environment if it is not properly treated (Lam & Lee, 2011) be it for discharge into a watercourse or land application, and without capturing the produced biogas. This could be further exacerbated if no effective waste management system is in place as currently there are some 454 palm oil mills in operation in varies states of Malaysia (MPOB, 2015; MPOCC, 2018).

To date, the POME discharge is being regulated through the Environmental Quality (Prescribed Premises) (Crude Palm Oil) Order, 1997 and Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations, 1997. They are promulgated under the Environmental Quality Act, 1974 enforced by Department of Environment(DOE). With this, the palm oil industry players are required to comply with the prescribed regulations i.e. 100 mg/L BOD limit before the effluent can be discharged into a watercourse. Recently, a stringent discharge requirement of BOD 20 mg/L level has been enforced by DOE to certain mills particularly in Sabah and Sarawak which are situated at environmentally sensitive areas, and some other areas in Peninsular Malaysia i.e. in Johor state (Liew et al., 2015).

In addition to that, DOE has also recently proposed a new regulation on POME discharge limit, of which the BOD limit will be lowered from 50 ppm to 20 ppm starting 1st of January, 2020 and thereafter. This has raised the industry players' concerns on the compliance issue of such regulation due to the current challenges facing them i.e. availability of technology, cost constraint and the lack of competent personnel in monitoring the POME treatment system. Although the results of POME survey for BOD 20 ppm initiated by MPOB in 2010 have shown the mills having POME polishing plant can achieve the proposed BOD limit, MPOB has suggested to remain the 50 ppm limit and discussion with DOE is underway (Astimar, 2018).

To achieve this, an effective treatment system which can consistently perform the required discharge limit is much sought after. Nevertheless, a higher cost could be incurred by the industry players dependent on the intention of either the quantity of wastewater is to be reduced or the effectiveness of wastewater treatment is to be enhanced. In regards to this issue, more attentions are paid on the latter option to safeguard a long run economic profit where this can be achieved if a more environmentally sound and economic viable wastewater treatment process can be established.

1.3 Background of the study and problem statement

The oil palm sector is currently facing many challenges and accusations from environmental and social aspects in the sector. Although many challenges faced by the oil palm industry have been overcome, there is still a need to address some challenges that are still prevalent that include proper documented system for identification of relevant laws and tracking any changes to the laws, palm wastes and wastewater management, and benefits and well-being of plantation workers. With a growing expectation in the global and regional markets for the production of sustainable palm oil, traceability and transparency must be demonstrated throughout the value chain of the palm oil production till the manufacturing of end product. Nevertheless, this requires full commitment and firm action from all stakeholders in the supply chain.

At present, Malaysian government is now setting the pace to change the way Malaysian palm oil producers produce palm oil, and putting in place the relevant regulatory requirements for the entire palm oil sector to demonstrate sustainability through MSPO certification. Based on the information documented by MPOCC (2018), the total area certified under MSPO certification as of October 2018 is 1,261614.76 hectares, which it can be accounted for 22% of the total oil palm planted area in Malaysia. Meantime, a total of 115 palm oil mills (25%) are now MSPO certified under the mill management certification. Apart from that, approximately of 85% of the RSPO certified entities have already been MSPO certified. Although many initiatives and efforts have been done to educate and inform these sectors on the importance and, value and benefits of obtaining MSPO certification, the MSPO certification uptake in Malaysia at present is still considered very low attributed to several factors including organization's perception of MSPO certification, high cost for certification, low awareness and understanding on the scheme among smallholders, extensive paper workload and land legality issues.

Associated with a low uptake of the certification in the sector, environmental management in those uncertified palm oil mills would remain insufficient and ineffective especially from the perspective of palm wastes management and wastewater treatment system i.e. POME treatment. Considering of the environmental damages that may inflict upon the production of million tonnes of palm wastes and wastewater i.e. POME in a palm oil mill, the current POME treatment system in Malaysian palm oil mills should be investigated to provide a feasible option on the selection of an effective wastewater technology adoption in the country.

When it comes to POME treatment, anaerobic digestion (AD) will automatically be acknowledged as the most efficient method because of its effective reduction of enormous amount of organic matters to an acceptable level before it is released into a watercourse (Borja et al., 1996a; Chen et al., 2015). In the AD process with the absence of oxygen (O_2), POME will be degraded into biogas consisting of methane (50-75%), carbon dioxide (25-50%) and a small amount of trace gases including hydrogen sulfide (H_2S), ammonia (NH_3) and hydrogen (H_2) under a series of hydrolysis, acidogenesis, acetogenesis and methanogenesis processes (Tchobanoglous & Burton, 1991; Polprasert, 1996). To date, various types of AD processes have been developed and they are suitable for POME treatment; e.g. attached growth anaerobic processes, continuous flow stirred tank reactor (CSTR), anaerobic blanket processes (such as up-flow anaerobic sludge blanket reactors and anaerobic baffled reactors), membrane separation anaerobic treatment processes and hybrid anaerobic treatment processes. Instead of selecting one suitable fit option from the available lists, by default, majority of the Malaysian palm oil mills have developed their own treatment systems which are tailor made and most feasible for POME after a series of consultation and consideration have been made.

According to Ma et al., (1993), Wu et al., (2010), Ahmad & Krimly (2014) and Nur Anira Syafiqah et al., (2018), more than 85% of the Malaysian palm oil mills are using the ponding system in treating POME due to a low capital cost investment. This has made the system becoming the most common method adopted in palm oil mills. Typically, this ponding system is consisted of wastes stabilization lagoons (anaerobic treatment) and oxidation ponds including aerobic, facultative and maturation ponds (Wong, 1980). Although the current ponding system is more economically viable, simple to operate and requires less maintenance, it occupies a large land area ranging from 1 hectare to 5 hectare and the hydraulic retention time (HRT) is longer (40 – 200 days) (Wong, 1980). However, this conventional method does not favor RE recovery as a huge amount of methane gas (CH_4) will be released into the atmosphere through the open top of the ponds/tanks. The global warming potential (GWP) of CH_4 is 25 times higher than carbon dioxide (CO_2) and therefore, huge emission of this gas will accelerate global warming (Gardner et al., 1993; IPCC, 2007). Additionally, such system has caused silting problem and much of the POME discharged into the watercourse has not been able to reach the standard discharge limit due to its short circuiting operation (Wu et al., 2010). This has affected the sustainability of the palm oil industry. Hence, instead of the conventional open ponding system, the enclosed AD system coupling with tertiary/polishing treatment which has found to significantly improve the organic matters content and acidity reduction of the POME is adopted and utilized (Yacob et al., 2006b; Ahmad & Chan, 2009; Abdurahman et al., 2011, Iskandar et al., 2018).

In Malaysia, the enclosed AD system either (1) covered lagoon biodigester system or (2) closed AD tank digester system, has been installed in some of the palm oil mills. In comparison to the open tank anaerobic digesters, these enclosed AD systems enable palm oil millers to capture the biogas and recover the containing energy as a supplementary boiler fuel and/or to be combusted in a biogas engine generator for power generation (Loh et al., 2013). In other words, the fossil fuels conventionally used for power generation in the mills can be displaced by the generated biogas and this subsequently facilitates GHG emissions reduction. In the meantime, the surplus electricity produced from biogas, if any, can be sold to the national Utility through the Distributed Grid System via a Feed-in Tariff (FiT) system (SEDA, 2014). This has made biogas harnessing a key solution to reduce dependence on fossil fuel, alleviate global warming and safeguard the environment.

Since biogas harnessing is in line with the government's strategy in RE implementation, the government has envisaged that all palm oil mills in the country to install biogas facility by 2020 under the eight core Entry Point Projects (EPPs) specifically in EPP 5 that is implemented by the Palm Oil National Key Economic Area (NKEA). In addition, new mills and mills requesting for throughput expansion are mandated to install full biogas harnessing or methane avoidance facility effective on 1st January 2014 (MPOB, 2013). However, based on the data documented by MPOB in 2014, only 67 out of 439 palm oil mills were recorded to have involved in biogas activities in Malaysia (Loh et al., 2014). With less than 20% uptake rate, the practicality of EPP 5 needs to be reassessed which could be related to high investment cost including biogas plant construction, the lacking of technical know-how and expertise, ineffective management of several biogas program and plans related to RE, and biodiversity concerns.

Although the main purpose of biogas harnessing is to protect the environment and natural resources, it is necessary to also secure the economic profit of the palm oil industry. Therefore, many research activities which especially focusing on the improvement of methane production to maximize economic benefits have been vigorously carried out in the country (Basri et al., 2010; Busu et al., 2010; Wang et al., 2015). However, there remains an issue on whether or not the biogas production is sustainable as its emissions has an effect on the environment just like any other kind of energy system. The public and some groups of the environmentalists have doubted on the reliability of such system in terms of the reduction of GHG emissions and fossil fuel dependency. Contrarily, the biogas players in the palm oil industry usually pay more attentions on how to make biogas harnessing more profitable rather than on environment conservation.

Moreover, different configurations of the biogas capture technology (i.e. AD tanks and covered lagoon) and biogas utilization (i.e. co-firing and grid connection) currently adopted in palm oil mills may lead to a great variance of outcomes in particular from the environmental and economic points of view. This situation could subsequently affect the selection and decision on an appropriate AD system among the palm oil industry players who acquire a cost-effective biogas capturing and utilization system associated with high and reliable performance. From this stand, it is assumed that different combination of biogas capture technology and utilization plays a significant role in facilitating sustainable development and economic growth of the palm oil industry. Hence, the palm oil industry players should take this into consideration when invest in biogas projects. To date, no rigorous guidelines and standards on technology adoption in treating POME in the country; which has made selection of biogas technology difficult among the majority of palm oil companies. The confusion created has resulted in a slow installation of biogas facility in the mills.

1.4 Research objectives of the study

Three objectives within the context of this study are required to be accomplished in order to advance the current deployment of POME-biogas business agenda, by formulating a case study consisting of four interest palm oil mills with different scenario of biogas facilities (see Section 3.1.1 for details). The rational for the selection of four interest palm oil mills as the case study is attributed to limited resources, data availability (data intensive), willingness of participation among palm oil mills and data transparency issue (millers' perception of LCA and economy status of the mill). The three specific objectives of the study are: 1) to determine the environmental impacts and costs incurred for eco-environmental conservation of the selected palm oil mills with current POME-biogas systems in Malaysia using LCA and ELCC approach, 2) to evaluate the environmental and economic performance of the selected palm oil mills with current POME-biogas systems in Malaysia, and 3) to develop an improvement assessment model for a better decision making among the palm oil industry players using Eco-costs/Value Ratio (EVR) model. The findings from this study may provide a baseline information on POME-biogas system with different configurations which could facilitate the industry players with optimal choices for environmental and economic improvement in their mills.

1.4.1 First research objective of the study

The first objective of the study is to determine the environmental impacts and costs incurred for eco-environmental conservation of the selected palm oil mills with current POME-biogas systems in Malaysia using LCA and ELCC approach. In palm oil milling processes, a huge amount of raw materials and energy are used to produce the main product i.e. CPO and co-products include palm kernel and shell. Meantime, other palm wastes including EFBs, boiler ash, POME and etc are massively produced as well. Although biogas capturing activity from POME treatment is conducted in the selected palm oil mills and biogas has been used for power generation i.e. either for the in house use or selling to national grid, it is uncertain that the GHG emission reduction through the biogas capturing activity itself is sustainable from the environmental perspective because its emissions has an effect on the environment similarly to any other kind of energy system. Besides that, many top managements of a palm oil mill will pay more attention on the cost components that may effect on their decision making for such investment when comparing to the environmental consideration. Therefore, determination of the environmental impacts through the analyzing of relevant inputs and outputs in terms of the life cycle perspective and cost incurred for such investment on different biogas configurations in the palm oil mills is important for looking into opportunities to reduce environmental impacts and operating and investment costs in a palm oil mill.

1.4.2 Second research objective of the study

The second objective of the study is to evaluate the environmental and economic performance of the selected palm oil mills with current POME-biogas systems in Malaysia. Evaluation of the environmental and economic performance of the selected palm oil mills is linked to the first objective of the study and it is made based on the life cycle perspective approach i.e. LCA and ELCC. In other words, it would have to take into consideration (1) the transportation of feedstock, (2) the biogas capture technology and biogas application, (3) the production and consumption of biogas, (4) the construction and demolition of the biogas plant itself, (5) the disposal of waste generated from the AD process, and (6) the economic evaluation of the biogas process into consideration while assessing the environmental and economic performance of the biogas production system of the selected palm oil mills. This is because all the activities mentioned above would change the mass and energy flows which then could affect fuel consumption, gaseous emissions and investment costs involved.

This kind of assessment is indispensable in order to obtain valid life cycle data for better evaluation towards the environmental and economic performance of a biogas production system in a palm oil mill. As such evaluation has not surfaced in the current landscape concerning sustainable development of POME-biogas production system. This situation has offered opportunity to research on comparative life cycle assessment using currently practiced different combination of technology on biogas capture and utilization via LCA and ELCC.

1.4.3 Third research objective of the study

The third objective of the study is to develop an improvement assessment model for a better decision making among the palm oil industry players using Eco-costs/Value Ratio (EVR) model. In some cases, palm oil mill with better environmental performance does not mean that the mill itself is economically viable or vice versa. Therefore, it is important to obtain a trade-offs between environmental and economic dimensions of sustainability because environment aspect alone is no longer sufficient to be used as a basis for sustainable development.

Considering this, the results obtained from the previous analyses as stated in the first and second objectives of the study will be analyzed, evaluated and drawn for making feasible recommendations using the EVR model; one eco-efficiency indicator that is used to reveal if a product system's consumption patterns is sustainable throughout its entire life cycle from the environmental and economic point of views. With this, it is hope that the findings of this study could provide a basis information for potential improvement to close certain sustainability gaps in a palm oil mill when the environmental impacts and cost incurred in the mills are identified.

1.5 Synopsis of the study

Before proceeding, a brief synopsis of the subsequent session of this thesis is introduced. In Chapter Two, relevant and detailed literatures and/or examples in relation to the employment of relevant environmental tools on biogas system and the key concepts guiding the analysis conducted in this study will be presented. Next, research framework and methodology used in this study including the scope/system boundary of the study will be described in Chapter Three. Subsequently, Chapter Four will present a detailed description on the findings and discussions of the study. Last but not least, the main conclusions and appropriate recommendations for guideline and practice development will be presented in Chapter Five.

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