School of Civil and Mechanical Engineering

Sustainability Assessment of Malaysian Palm Oil Industry

Chye Ing Lim

This thesis is presented for the Degree of

Doctor of Philosophy

of

Curtin University

July 19

To my parents

DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Chye Ing LIM

14 July 2019

ABSTRACT

Palm oil is a controversial subject worldwide. It is commonly blamed for causing deforestation, loss of biodiversity, pollution and social inequity between palm oil industry and the indigenous people. On the other hand, it is a relatively high yield, nutritious, versatile yet cheap oil crop that is much needed to solve the food and energy problem to attain sustainable future. Whist palm oil production causes various impacts on the environment and people, it contributed significantly to the economic growth of Malaysia for the past three decades. Malaysia is also regarded as the second largest palm oil producer in the world. In order for Malaysian palm oil industry to meet the stringent market demand for sustainably produced oil products, it is important for palm oil industry to continuously examine processes in its supply chain to improve its sustainability.

In this research, sustainable palm oil was defined to develop an assessment framework and the weaknesses associated with existing sustainability assessment methods toward sustainable palm oil production were investigated. Subsequently, a sustainability assessment framework was developed and applied to evaluate and improve the sustainability performance of a Malaysian crude palm oil supply chain, including oil palm nursery, oil palm plantation and palm oil mill.

This is a publication-based research consisting of 5 refereed journal papers addressing 5 different specific objectives of this PhD research in attaining the goal of sustainable palm oil production in Malaysia.

The research found that the palm oil supply chain should be assessed against sustainability criteria that is built on strong sustainability principle, covering triple bottom line aspects of sustainability that does not trade off ecological and intra and inter-generational social equity for economy development. The assessment should be able to identify sustainability hotspot in order to determine the right strategies for achieving sustainability thresholds. The literature review reflected that the palm oil production in Malaysia is economy-driven but there are other environmental, economic and social sustainability aspects that need further assessment to measure their implications on the sustainability performance of the upstream processes of the palm oil supply chain. Existing tools, standards and legislative requirements that were so far applied in the supply chain to assess sustainability performance are lacking in terms of 1) comprehensiveness in assessing all Triple Bottom Line objectives; 2) selection of indicators based on strong sustainability objectives, 3) transparent and inclusive selection process; 4) specific and quantifiable sustainability outcome for each indicator. Hence, there is a need for the development of a holistic, comprehensive sustainability assessment framework that allows to measure true sustainability performance of crude palm oil production for decision making as well as for further improvement of the supply chain.

A Palm Oil Sustainability Assessment (POSA) framework was developed based on a strong sustainability concept that measures all dimensions of Triple Bottom Line. It applies an integrated approach using a multi-criteria analysis with indicators that are arranged in the triangular structure. In this framework, the overall sustainability performance of the palm oil supply chain was segregated into three sustainability objectives i.e. environmental, economic and social. The Headline Performance Indicators (HPI) of each of these three sustainability objectives were identified and each of these HPIs consists of Key Performance Indicators (KPI). Specific Performance Measures (PM) that were quantifiable/ semi-quantifiable were listed for each KPI. The PM was rated on a Likert scale of 1 – 5 where 5 was the threshold value of the PM to be sustainable. Ranking criteria for every PM were based on literature review and relevant government legislations. The sustainability gap for PMs, KPIs, HPIs, sustainability objectives and overall sustainability performance is the difference between the ranking value and 5.

The initial set of indicators were listed based on the literature review and then the collective feedback on the relevance and importance of these indicators were gathered from the government, industry, academia and local smallholders/ NGOs. The inputs of these stakeholders were used to ascertain the weight for each Performance Measure to establish a scientifically valid assessment framework.

The framework was later tested successfully on the ground to assess the sustainability of the crude palm oil production for the most common supply chain in Malaysia. The data was collected from the supply chain, where oil palms were planted on mineral soil, located in Borneo Island of Malaysia and the oil mill did not have a biogas trapping system for palm oil mill effluent treatment. The results from the assessment showed that the overall sustainability performance of the supply chain was below the sustainability threshold (i.e. 3.47/5). The assessment indicated a need of improvement in environmental performance measures e.g. greenhouse gas emission, plantation practices, biomass waste recycling and recovery. The suggestions for improving economic sustainability performance are to have bigger smallholder equity, higher average wages and increase in local employment to ensure sharing of economic benefits with the local community. The POSA framework was also applied to an improved supply chain with a biogas trapping system incorporated in order to examine the flexibility of the framework. The results showed that the framework was able to capture the changes of the triple bottom line indicators due to incorporation of an improvement strategy into the existing supply chain. Incorporating biogas trapping system into the supply chain was found to improve the overall sustainability performance from 3.47/5 to 3.59/5, by eliminating hotspots of greenhouse gas emission and biomass waste recycling and recovery.

Finally, the POSA framework addresses some of the weaknesses of existing assessment methods by allowing holistic, comprehensive assessment of the crude palm oil supply chain for self-assessment as well as for continuous improvement to attain a more sustainable crude palm oil production.

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Thank you.

GLOSSARY

AGR	Actual Growth Rate
AR5	5th Assessment Report
BGPP	Biogas cum Polishing Plant
BOD	Biochemical Oxygen Demand
CHP	Combined-heat and Power Unit
CO_2eq	Carbon dioxide equivalent
COD	Chemical Oxygen Demand
CPO	Crude Palm Oil
DOE	Department of Environment
EFB	Empty Fruit Bunches
EU	European Union
FFB	Fresh Fruit Bunches
FPIC	Free, prior and informed consent
FU	Functional Unit
GHG	Greenhouse gases
Ha	Hectare
HPI	Headline Performance Indicator
HCVF	High conservation value forest
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
m^3	cubic meter
mg/L	Milligram per litre
MJ	Mega joule
MT	Metric tonne
MT/hr	Metric tonne per hour
MPOB	Malaysian Palm Oil Board
MSPO	Malaysian Standard on Malaysian Sustainable Palm Oil

Nm^3	Normal Cubic Meter
NO_x	Nitrogen Oxides
NPK	Nitrogen, Phosphorus and Potassium
PAC	Poly-aluminium chloride
PM	Performance Measure
POME	Palm Oil Mill Effluent
POSA	Palm Oil Sustainability Assessment Framework
RSPO	Roundtable on Sustainable Palm Oil
SGR	Sustainable Growth Rate
SO_x	Sulphur Oxides
TBL	Triple Bottom Line

LIST OF PUBLICATIONS INCLUDED AS PART OF THE THESIS

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Peer-reviewed Paper Published in Indexed Journal

The publications listed below are reproduced in full in Appendices 1 – 5

Paper 1

Lim, C. I., Biswas, W., & Samyudia, Y. (2015). Review of Existing Sustainability Assessment Methods for Malaysian Palm Oil Production. *Procedia CIRP, 26*, 13-18. doi:10.1016/j.procir.2014.08.020

Paper 2

Lim, C. I., & Biswas, W. (2015). An Evaluation of Holistic Sustainability Assessment Framework for Palm Oil Production in Malaysia. *Sustainability, 7*(12), 16561-16587. doi:10.3390/su71215833

Paper 3

Lim, C. I., & Biswas, W. K. (2017). Development of triple bottom line indicators for sustainability assessment framework of Malaysian palm oil industry. *Clean Technologies and Environmental Policy*, 1-22. doi:10.1007/s10098-017-1453-7

Paper 4

Lim, C.I., & Biswas W.K. (2018). Sustainability assessment for crude palm oil production in Malaysia using the palm oil sustainability assessment framework. *Sustainable Development*, 1–17. doi.org/10.1002/sd.1872

Paper 5

Lim, C. I., & Biswas, W. (2019). Sustainability Implications of the Incorporation of a Biogas Trapping System into a Conventional Crude Palm Oil Supply Chain. *Sustainability, 11*(3), 792; doi: 10.3390/su11030792

Registered Patents

The following patent application was filed as part of the output the doctoral study. Refer **Appendix 6**

Lim, Chye Ing, and K. Biswas Wahidul. 2017. Palm Oil Sustainability Assessment (POSA) Framework. edited by Intellectual Property Corporation of Malaysia. Malaysia.

STATEMENT OF CONTRIBUTION AND CO-AUTHORSHIP DECLARATION

I hereby declare that I have authored and co-authored the following publications. The level of my intellectual input to each publication is indicated in brackets as below. Signed verification statements from each of my co-authors are provided in Appendices 1-5.

Ms. Chye Ing Lim   Associate Professor Wahidul Biswas (Supervisor)

Lim, C. I., Biswas, W., & Samyudia, Y. (2015). Review of Existing Sustainability Assessment Methods for Malaysian Palm Oil Production. *Procedia CIRP, 26*, 13-18. doi:10.1016/j.procir.2014.08.020 (80% contribution by lead author/PhD candidate)

Lim, C. I., & Biswas, W. (2015). An Evaluation of Holistic Sustainability Assessment Framework for Palm Oil Production in Malaysia. *Sustainability, 7*(12), 16561-16587. doi:10.3390/su71215833 (80% contribution by lead author/PhD candidate)

Lim, C. I., & Biswas, W. K. (2017). Development of triple bottom line indicators for sustainability assessment framework of Malaysian palm oil industry. *Clean Technologies and Environmental Policy*, 1-22. doi:10.1007/s10098-017-1453-7 (80% contribution by lead author/PhD candidate)

Lim, C.I., & Biswas W.K. (2018). Sustainability assessment for crude palm oil production in Malaysia using the palm oil sustainability assessment framework. *Sustainable Development*, 1–17. doi.org/10.1002/sd.1872 (80% contribution by lead author/PhD candidate)

Lim, C. I., & Biswas, W. (2019). Sustainability Implications of the Incorporation of a Biogas Trapping System into a Conventional Crude Palm Oil Supply Chain. *Sustainability, 11*(3), 792; doi: 10.3390/su11030792 (80% contribution by lead author/PhD candidate)

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CHAPTER 1. INTRODUCTION

1.1. Introduction

This thesis presents the development and application of a palm oil sustainability assessment (POSA) framework in addressing sustainability challenges associated with the production of crude palm oil in Malaysia. A rigorous literature review followed by a consensus conference involving local experts were carried out to develop social, economic and environmental indicators to measure as well as to improve the sustainability performance of this industry using the POSA framework.

1.2. Background

If there is a question, *"what is the most important crop to Malaysian?"*, the answers would definitely be oil palm[1]. The development of Malaysian palm oil industry started to pick up rapidly in the 1980s, by gradually replacing less lucrative crops during that time such as rubber and cocoa (1). Oil palm plantations are now commonly seen across Malaysia covering almost 5.8 million Ha until 2017 (Figure 1.1) (2, 3). This industry uses 17.6% of the Country's land and accounts for 43.1% of the RM89.5 billion (USD22 billion) Gross Domestic Product (GDP) for the agriculture industry. This share is significantly higher than livestock (11.6%), fishing (11.5%), forestry & logging (7.2%), rubber (7.1 %) and other agricultural (19.5%) sectors in the country (4). The palm oil supply chain employs annually around 800,000 people (4-6) In addition, the livelihood of 650,000 local smallholders heavily depend on this industry (7). The involvement of local planters in palm oil plantation was found to alleviate poverty, and improve healthcare and education of the rural community (8). This snapshot highlights the significance of palm oil industry to the Malaysia's landscape, economy and the wellbeing of its people.

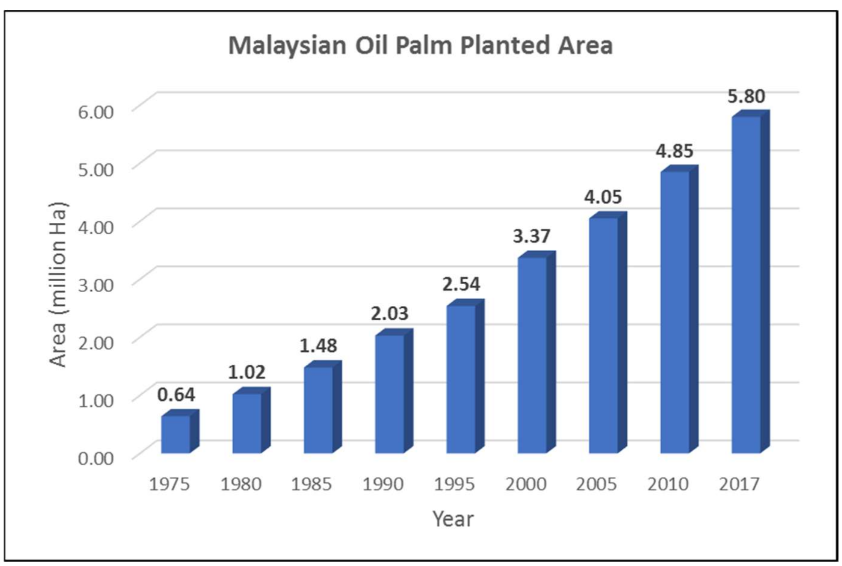

Figure 1.1: Malaysian Oil Palm Planted Area (Million Hectare) (2, 3)

[1] Oil palm refers to the oil palm tree while palm oil refers to the oil extracted from its fruits

The growth of palm oil industry over the last decades has been accelerated by a number of factors. Palm oil is one of the top seventeen oil and fat sources in the world (9), and also it is enriched with antioxidants particularly β-carotene and vitamin E (10). In 2016/2017, global palm oil production (61 million MT) contributed to 31% of the total demand for vegetable oil and fats, bypassing other important oil crops such as soybean oil, sunflower seed oil, peanut oil and rapeseed oil. The lower production cost of palm oil is another reason of its increased market share. It is cheaper (up to USD 200 per tonne) than other competing vegetable oils, including rapeseed oil, groundnut, sunflower and soybean (1). The yield of oil palm (tonne/Ha) is about 10 times more than other leading oilseed crops, which offer high land use efficiency in this ever-crowded world. As a result, it contributes to 57% of world vegetable oil exports, and is three times more tradable compared to soybean. Palm oil has so far met the edible oil needs of 3 billion people in 150 countries (9).

Palm oil is versatile, not only a major oil and fat source but it is also used extensively as a raw material for oleo-chemicals and biofuel production (11). Malaysia has started the production of B5 (i.e. 5% palm oil in biodiesel) and B7 (i.e. 7% palm oil) biofuel blend in 2014. The production of palm oil based biodiesel was 720,410 tonnes in 2017 (12). The use of palm oil based biofuel could offer significant carbon saving benefits (i.e. avoidance of approximately 3 tonnes of carbon dioxide emission per vehicle per year) in a carbon constrained global economy by replacing petroleum fuel (13) and slow down the depletion rate of non-renewable fossil fuels to address oil scarcity.

Despite these economic, social and environmental sustainability benefits of palm oil production, the international pressure groups, including Greenpeace, Rainforest Action Network and World Wildlife Fund (WWF) have identified some environmental problems and socially inequitable issues of these production activities (14). The industry was blamed for causing deforestation and the loss of species due to its monoculture plantations, intensive farming practices and unplanned land use (e.g. large-scale plantation usually does not consider landscape heterogeneity). Open and slash burning of trees to create space for oil palm plantation has led to serious forest and land fire over the past decades in palm oil producing nations, Indonesia and Malaysia. The fire caused haze problem to whole South East Asian region for couple of weeks. The air pollution had not only affected the health and daily life of the people but it also caused tremendous economic loss (e.g. closing of schools and offices, increased medical cost for treatment of respiratory illnesses). For example, fire and haze in Indonesia in 2015 contributed to an economic loss of USD 16.1 billion, 24 casualties and 100,300 cases of preliminary deaths. Twenty percent of this fire happened in the oil palm plantation area (15, 16).

The application of large amount of N-fertiliser, synthetic chemicals (e.g. pesticide and herbicide) in oil palm plantations caused the release of powerful greenhouse gas (i.e. N_2O), and increased soil and water pollutions (i.e. eutrophication) (17). The consumption of fossil fuel for machineries at plantation sites and palm oil mills resulted in atmospheric emissions (e.g. CO_2, CO, NO_x and SO_x) and an increased pressure on imported fossil fuels. Besides, palm oil mill effluent (POME) waste with high concentration of organic matter is usually disposed to open pond for treatment, which not only releases powerful GHG emissions (i.e. CH_4,, which is 28 times more powerful than CO_2)(18), but also produces a strong 'rotten-egg' odour that could affect the receptor located within a radius of 1.3km around the mill (19). As of December 2016, 357 out of 449 palm oil mills in Malaysia (79.5%) were still using open ponding system to treat POME (20).

Sustainability record of palm oil industry is also tainted with cases of social conflict between local community and plantation companies. It was reported that the local indigenous people in some places were forced to accept unfair land acquisition. The palm oil company did not provide Free, Prior and Informed Consent (FPIC) to this local community through consultation and also no agreement was signed before converting the native customary land into large oil palm plantations (21-23). Last but not least, air, ground and water pollutions caused by the palm oil supply chain have also affected the local communities to access forest resources (i.e. wildlife and edible plants) and their source of protein was hampered due to the reduction in the number of fishes in the polluted river (i.e. eutrophication) (8).

These issues drew the attention of some food manufacturing giants demanding for sustainable palm oil production (14, 24, 25). Also, one of the major palm oil importers, the European Union has already capped palm oil based fuel at 2019 levels until 2030 and then its use will ultimately be banned by 2030 (26). The implication of this strategy is expected to drop palm oil export of Malaysia by 10.9% (27). Malaysia is thus under pressure to produce palm oil by addressing these triple bottom line sustainability challenges.

There is no doubt that palm oil is vital to meet the world's demand for food, renewable feedstock for energy and oleo-chemical products. Banning palm oil would leave a large void in solving the food and energy problems to achieve sustainable future. Thus, it raises a more practical question as to how Malaysian palm oil industry can continue its palm oil production in a sustainable manner to meet the growing demand for food and fuel.

1.3. Problem Statements and Research Questions

'Sustainable palm oil' specifically for Malaysia's situation needs to be defined to set a sustainability target for the palm oil industry. A holistic assessment method needs to be developed to assess sustainability of palm oil production in a Specific, Measurable, Attainable, Relevant and Timely (SMART) manner, and to provide guideline for sustainable palm oil production. This poses the following research questions: -

- What is sustainable palm oil production?
- What are some drawbacks in the existing assessment methods that need to be addressed in evaluating and improving sustainable palm oil production?

- What could be a holistic framework in assessing and improving sustainable palm oil production?

1.4. Goal, Specific Objectives and Scope

The Goal of this research is to attain sustainable palm oil production in Malaysia using an appropriate sustainability assessment framework. To achieve this goal, following four research objectives have been achieved through five journal article publications.

Objective 1: Paper 1 (Lim, Biswas (28))– The Review

- *To investigate sustainability aspects of palm oil supply chain in Malaysia, as well as to review existing sustainability assessment methods/ tools that were currently being used to address this situation in order* to *identify the research gap of this PhD work.*

The literature review formed the major part of the scope of this doctoral research. The Triple Bottom Line (i.e. Environment, Economy and Social) aspects of the palm oil industry in Malaysia were reviewed. The review identified the need for sustainability assessment, and the key areas of concerns. Sustainability theories and concepts were also reviewed from the context of palm oil production, in order to define sustainable palm oil production for Malaysia. Accordingly, the existing palm oil sustainability assessment methods and tools used in the palm oil supply chain were reviewed and analysed to identify strengths and weaknesses of these methods and tools, which in fact necessitated the need for development of a framework to achieve sustainable palm oil scenario. The research gap generated from this literature review concluded that there is a need for a holistic, comprehensive sustainability assessment framework to comply with the definition of sustainable palm oil production. Besides, the scope of this sustainability assessment framework was kept limited to crude palm oil production, where most impacts occurred. It did not consider downstream activities including refinement of crude palm oil for different applications such as biofuel, vegetable oil, cosmetics etc.

Objective 2: Paper 2 (Lim and Biswas (29)) & Paper 3 (Lim and Biswas (30))– The Theoretical Framework

- *To develop a holistic sustainability assessment framework for achieving environmental, economic and social objectives of crude palm oil supply chain in Malaysia.*

Firstly, the development of the sustainability assessment framework involved the identification of system boundary of the assessment framework. The processes of the supply chain were identified for inclusion into the assessment framework. Additional literature review and analysis were carried out on various sustainability assessment methods and structures that were used globally in order to come up with a framework, suitable for the sustainability assessment of Malaysian crude palm oil supply chain. The framework was developed in two stages:

i. Initial structure of the framework explained how performance measures (PMs), key performance indicators (KPIs), headline performance indicators (HPI) of sustainability objectives have been integrated to determine social, economic and environmental objectives of crude palm oil production. The limitations were, i) indicators were not weighted and ii) the scientific justifications of their use were not considered.
ii. A consensus on the selection of PMs was achieved through collective feedback from stakeholders of various roles and backgrounds along the supply chain, because the importance and relevance of PMs vary with places, culture, geography and socio-economic situations.

Lastly, the effectiveness of the assessment framework was tested using hypothetical data and any potential problems that arose were sorted out by revising the equations and threshold values of indicators. This was how the Palm Oil Sustainability Assessment (POSA) Framework was developed and then patented (Patent Number PI 2017704083) **Appendix 6 – Patent Registration**.

Objective 3: Paper 4 (Lim and Biswas (31)) – The Application of POSA Framework

- *To apply the palm oil sustainability assessment (POSA) framework for assessing the sustainability performance of crude palm oil production in Malaysia.*

The Palm Oil Sustainability Assessment (POSA) framework was applied to assess the sustainability performance of the most common crude palm oil supply chain of Malaysia in Borneo Island. Firstly, a comprehensive site-specific data collection was conducted along the supply chain. The supply chain includes oil palm nursery, large and small plantations and palm oil mill. These primary data were used to calculate the quantitative values of PMs. Some of the PMs (e.g. species loss, level of community acceptance to plantation and mill activities) were also rated/ ranked based on the collective feedback from the local stakeholders. Secondly, the PMs were ranked against the ranking criteria, and the ranking value was multiplied by the corresponding weight of each PM to determine the score of each PM. The scores of PMs were aggregated to corresponding KPIs, and then the scores for KPIs were aggregated to corresponding HPIs, subsequently the scores for HPIs were aggregated to determine the performance of social, economic and environmental objectives. Lastly, these three objectives were integrated into a single sustainability score. The score for the most common crude palm oil supply chain of Malaysia located in Borneo Island was estimated and the "sustainability hotspots" or areas that required significant improvement for sustainability performance were identified.

Objective 4: Paper 5 (Lim and Biswas (32)) – The Flexibility of POSA Framework

- *To investigate how POSA can handle any changes associated with the incorporation of improvement strategies in the supply chain.*

An environmental improvement strategy was incorporated into the crude palm oil supply chain to assess the improvement in the sustainability performance using the POSA framework. The input data of the improvement strategy were incorporated into an existing crude palm oil supply chain to investigate any changes in PMs, as well as to see if there is any increase or decrease of the overall sustainability score. Thus, the flexibility of the POSA framework was tested not only to improve the overall sustainability score and capture changes associated with the incorporation of new strategies, but also to identify some PMs that were negatively affected due to these changes in the supply chain. This framework could thus allow a number of iterative processes involving a variety of TBL improvement strategies until a strong sustainability scenario is achieved.

1.5. Research Methods

The research method consists of developing an initial model using a comprehensive literature review, stakeholders' survey, interview, site visits, case studies, Life Cycle Assessment (LCA) and quantitative analyses.

Rigorous literature review was carried out to list a set of TBL indicators for measuring environmental, economic and social sustainability objectives, as well as to determine the threshold values for these indicators. The hypothetical data were used for testing of the initial framework prior to the field test. The literature review included official databases (e.g. the Intergovernmental Panel on Climate Change (IPCC) emission factor database, and the Malaysian Palm Oil Board (MPOB) statistics, articles published in national newspapers and magazines, organizations' websites, published surveys, national statistics documents, official reports, palm oil related directives, legislations and standards as well as refereed journal papers in English that were published over the last 10 years.

The TBL indicators vary with regions, socio-economic conditions, and resource utilization and therefore, a stakeholder survey was conducted to gather collective feedback from government, industry, academics and local people/ non-government organisation activists in selecting the indicators as well as to provide weights to these indicators. The participants' information statement and questionnaires were approved by the Curtin Research Integrity Committee (approval number of HRE2016-0267 - **Appendix 7**). The survey was conducted online and also by delivering hardcopy of the questionnaire, based on participant's preference and their accessibility to the internet. The survey was conducted on a voluntary basis, where the identity of the participant was not disclosed.

The POSA framework uses a Likert-scale of 1 – 5 to rank the sustainability performance of each indicator (i.e. PM) used in the framework, where 5 is the sustainability threshold to be achieved. A series of mathematical equations were developed in this research to establish the relationship between different levels of indicators, and to calculate the overall sustainability score. These equations were used to calculate, interpret and evaluate primary and secondary data collected from the industries in the supply chain. The data analysis was conducted in Microsoft Excel spreadsheet. The framework identified the PMs or sustainability hotspots mainly responsible for lowering the overall performance. Therefore, it was modelled in a way that the new strategies can be incorporated to further improve the sustainability performance.

The assessment framework has thus been developed for its real-world applications. Referring to the statistic of Malaysian crude palm oil supply chain, a representative supply chain was chosen based on criteria, including location, type of plantations, source of Fresh Fruit Bunches (FFB), type of technology used in the palm oil mill, in order to apply this framework. The industries and local stakeholders in the supply chain provided actual operational data on a voluntary basis on the condition that their identities would remain undisclosed.

Site visits and personal interview with the stakeholders of the supply chain were conducted during the stakeholder's survey and site-specific data collection. This process enabled the author to clarify queries during data collection, and to have a better understanding on the site condition. The essential data that was not possible to obtain from the field were obtained from the literature.

1.6. Significance

This research could offer significant sustainability benefits to palm oil industry in Malaysia in a number of ways. Firstly, the research provides a definition of sustainable crude palm oil production specifically for Malaysia. Secondly, this research identifies the shortcomings of existing methods/ tools for achieving the sustainability of palm oil production in Malaysia.

Thirdly, the sustainability assessment framework will assist stakeholders in the crude palm oil supply chain to assess the TBL implications of production processes thus enabling them to make decisions on strategies for improving the overall supply chain sustainability performance. The restructure of crude palm oil supply chain through sustainability performance improvement will strengthen the market of Malaysian palm oil across the globe.

Lastly, the stakeholders in the supply chain will be aware of positive and negative consequences associated with the incorporation of new improvement strategies in the supply chain of crude palm oil production.

1.7. Limitations of the Research

Some limitations of the research are defined as follows:

- The scope of POSA framework is currently limited to the upstream stages of palm oil production, from nursery to palm oil mill for crude palm oil production.
- The TBL indicators selected for this POSA framework were specifically identified for the Malaysian palm oil supply chain. The relevance and importance of these TBL indicators should be reviewed if the POSA framework is applied in the context of other palm oil producing countries.
- The ranking criteria and threshold of PMs are site-specific based on the Malaysian's legislation requirements, agreement in international treaties, national statistics (e.g. average income in determining relative poverty level), and published research articles. The ranking criteria and threshold values of PMs and even some of the PM considered in this research cannot be considered for other countries due to the variation resource utilization and socio-economic situations. The technological change in the future could alter some of these indicators and sustainability threshold values.
- The relevance of indicators could change over time due to policy changes and changes in Malaysia's socio-economic and environmental situation. This future scenario analysis as to how the PMs and the sustainability assessment will vary over time is beyond the scope of this research.
- Some PMs could have been measured using equipment (e.g. measuring soil nitrate levels directly with a flow injection analyser instead of using it pH in the waterway) on the ground, but again, this is beyond the scope of this work.

1.8. Thesis Outline

Figure 1.2 illustrates the outline of this thesis showing how 5 journal papers published from this PhD work have addressed 4 research objectives to attain sustainable crude palm oil production in Malaysia.

Chapter 1 gives the significance of the research and clearly spells out the goal, specific objectives and scopes of these objectives. Also, it highlights the method, significance and limitations of the overall research.

Chapter 2 (or Paper 1) presents the literature review of sustainability implications of palm oil production in Malaysia, concepts and definitions of sustainable palm oil, existing sustainability assessment methods applied in the palm oil industry, in order to determine the research gap so that an appropriate sustainability assessment framework can be developed to achieve sustainable palm oil production.

Chapter 3 illustrates the processes in developing the methodology i.e. the assessment framework for sustainable crude palm oil production in Malaysia (Paper 2). The design and development of the framework were further revised (Paper 3). The effectiveness of the framework was tested with hypothetical data, most of which were gathered from literature and few of them were based on local knowledge.

In Chapter 4 (or Paper 4), the framework was tested using actual site-specific data from the most common crude palm oil supply chain in Malaysia. The selection of the supply chain was followed by data collection and the discussions on sustainability assessment outcomes. The sustainability hotspots were identified using this POSA framework to devise potential sustainability improvement strategies.

Chapter 5 presents the description of the improvement strategy that was incorporated into the supply chain, the collection of additional data for this new strategy, and a comparative analysis of sustainability assessment results of supply chains with and without the incorporation of the improvement strategy. The chapter (i.e. Paper 5) shows the implication of the improvement strategy on the supply chain. Finally, it confirms the flexibility of the assessment framework in terms of capturing associated changes in the supply chain due to incorporation of new strategies.

Finally, Chapter 6 summarises how 4 objectives were addressed through 5 journal publications written from this PhD research.

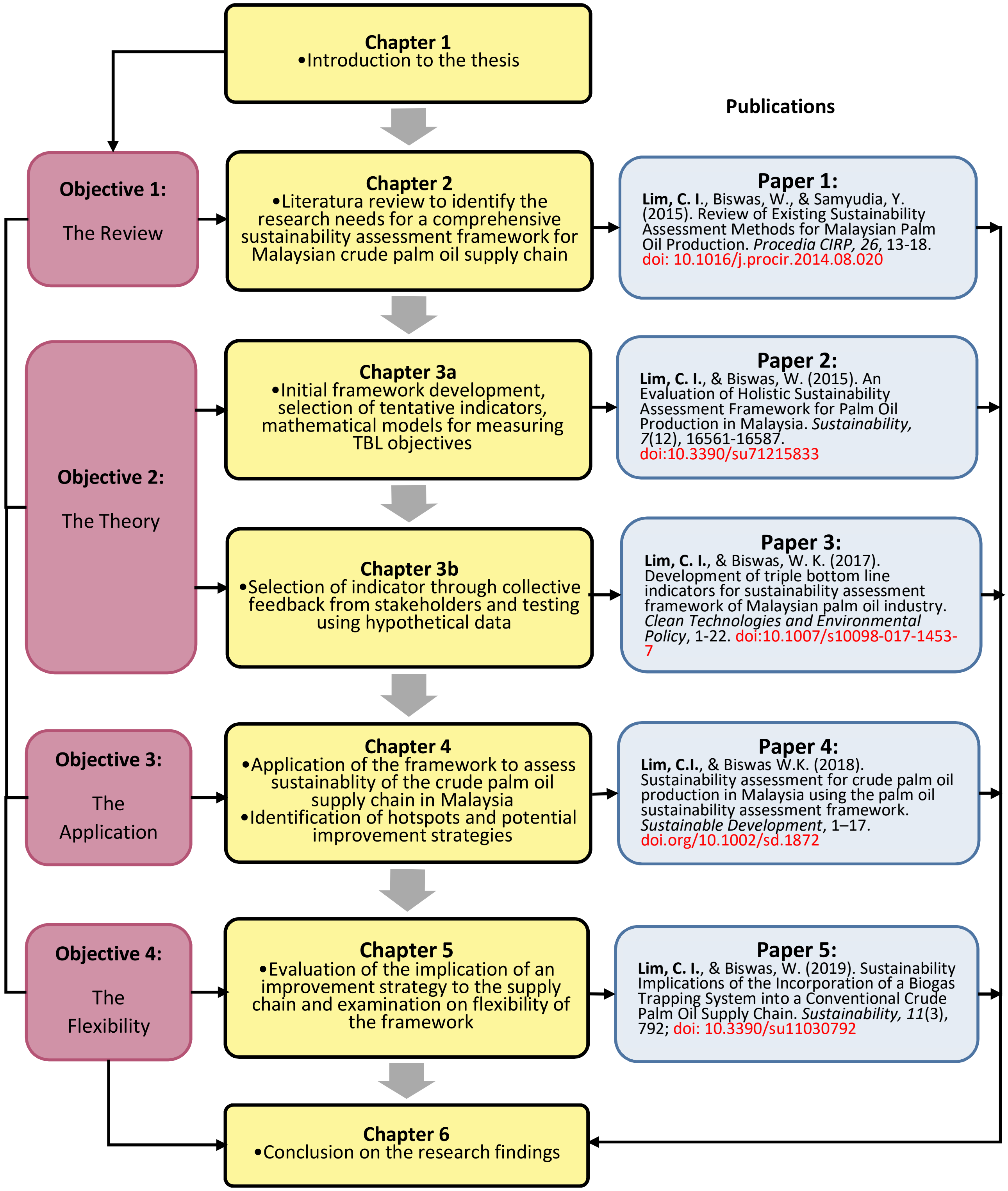

Figure 1.2: Thesis Outline

Note: PhD Candidate Lim contributed 80% to aforementioned published papers

CHAPTER 2. LITERATURE REVIEW

2.1 Background and Objective

The objective of this chapter is to review sustainability issues associated with palm oil production in Malaysia and the existing methods and tools for sustainability assessment of this production to identify the research gap or the areas for further improvement of the assessment process.

The journal version of this chapter entitled “Review of Existing Sustainability Assessment Tools for Malaysian Palm Oil Production” is included in **Appendix 1 – Paper 1** (28).

2.2 Review of Malaysian Palm Oil Production

The review was conducted to capture the triple bottom line (TBL) or environmental, economic and social implications of palm oil production in Malaysia as discussed in Section 3 of Paper 1 (28). The palm oil offers better economic performance than other oilseed crops due to its higher oil yield (litre/Ha) and energy yield ratio (Output/Input energy). It is not only an important food source, but also a renewable fuel feedstock to produce biofuel to replace conventional fossil fuel and to reduce combustion related GHG emissions. However, palm oil production is not entirely free from environmental impacts as it causes the loss of biodiversity, peatland and forest fire, on-farm GHG emissions, and soil and water pollutions.

The palm oil industry empowered the rural community through job creation, and offered independent smallholders’ schemes (e.g. the Oil Palm Industry Mechanization Incentive Scheme where smallholders were given subsidy by the government to purchase plantation equipment), to reduce urban migration, improve education and healthcare of the local people. The downside of this plantation practice was that the local indigenous people had lost their traditional lifestyle and livelihoods such as hunters and gatherers. The oil palm plantations also took away their native customary land, destroyed their cultural heritage and ancestral burial ground. The forest and river resources that provided sustainable livelihood for the local people was significantly reduced due to water pollutions and monoculture plantations. Conflicts and social inequity were found to exist particularly in the upstream stages of palm oil production, where local people were less empowered to reach a fair agreement with the industry owner in terms of land deals, workers’ welfare (e.g. healthcare insurance, transportation subsistence, better living quarters) and wages.

This palm oil industry now experiences an enormous business risk of market failure due to increased consumer’s demand for socially responsible and sustainably produced products. This situation could badly affect the Malaysia’s economy, as this industry contributes to significant share (3rd largest contributor; 3.82% in 2017) of the nation’s GDP. Because of adverse environmental consequences, pressure groups and green consumers have begun to campaign for banning the use of palm oil completely. The government agencies in the U.S and Europe had applied stringent conditions on the imported palm oil for food and biofuel production, which led to the fall of palm oil demand. Also, the European Union has started to cap the use of palm oil in automobiles this year (2019). Consequently, the market price of palm oil dropped from RM2801 per tonne in November 2017 to RM1984 per tonne in November 2018; with an annual decrease of 29%, due to reduction in market demand. This had caused cascading effects as the supporting businesses and the local people at the plantation site were affected (33). Smallholders in particular, are the main victims as it affected their income and livelihoods (34).

This literature review on aforementioned TBL aspects had generated following definition of sustainable palm oil production to address sustainability challenges associated with Malaysian crude palm oil production.

> *"the production that does not cause the loss of bio-diversity, does not increase GHG emissions and associated ecological footprints, does not affect the livelihood of the indigenous people; while enhancing commercial operation, sharing economic growth with the local community through employment and fair trade (28)."*

This definition had in fact formed the basis for reviewing the existing sustainability assessment methods/ tools used globally for addressing sustainability of palm oil production in Malaysia in subsequent sections of the published paper *(28)*.

2.3 Review of Existing Sustainability-Related Assessment for Palm Oil Production

Sections 4 and 5 of Paper 1 (28) reviewed existing sustainability-related assessment methods and standards applied by the industry to measure the sustainability of palm oil production. These include life cycle assessment (LCA), palm oil sustainability standards and certification schemes, as well as trade requirements and directives of importing countries.

The Malaysian Palm Oil Board conducted a full LCA of palm oil production to identify the largest impact resulting from the upstream processes of the supply chain. However, it only determined the single score for overall environmental impacts instead of providing the breakdown of this score in terms of impact categories. Secondly, the system boundary of this LCA excluded land use changes, which could affect the accuracy of carbon footprint estimation. Most importantly, LCA was not considered for measuring economic and social objectives of sustainability.

Palm oil sustainability standards and certification schemes including RSPO (Roundtable Sustainable Palm Oil), MSPO (Malaysian Sustainability Palm Oil) and ISCC (International Sustainability and Carbon Certification) on the other hand, have their own TBL assessment criteria for assessing environment, social and economic objectives. However, these criteria are broad and they were used mainly for certification purposes only. Thus, there exists a need for a comprehensive framework utilizing specific and quantifiable sustainability performance indicators and then to determine strategies for further sustainability improvement.

The drawbacks of aforementioned schemes are the selection of weak indicators pertaining to ecosystem conservation, where banning on peatlands and high carbon stock forests were not clearly specified. The certification board membership was dominated by industrial players, and thus there is a question of accountability. Some of the schemes that were endorsed by RSPO, was found to be blamed for greenwashing. The GreenPalm certificate scheme endorsed by RSPO allows manufacturer and retailer to purchase the certificates from the RSPO certified growers to fund sustainably produced palm oil and promote their product as environmentally friendly (35). However, this process does not actually require the manufacturers or retailers to source palm oil from the certified supply chain (14, 36). Also, RSPO's existing certification programme allows plantation companies to produce palm oil in both sustainable and unsustainable manner. This is because RSPO certifies the plantation areas, but not the company. So the company could have sustainable plantation area just to meet the demand for sustainable palm oil, while continuing unsustainable plantations on another site for the market where there is no requirement for the RSPO certified palm oil (37). Therefore, RSPO was sometimes criticised for not being sustainability driven.

Trade requirements and directives of importing countries (i.e. the United States' Renewable Fuel Standards 2 (RFS2) and European Union Renewable Energy Directives) set standards to measure some sustainability related indicators for palm oil. These indicators included the ban on palm oil produced in high carbon stock and biodiversity area, GHG saving from the use of palm oil-based biofuel. These requirements, however, do not consider social and economic objectives of sustainability. Thus, the review clearly concludes that there is an absence of holistic approach in assessing sustainability of Malaysian palm oil industry. Also, there is a need for a framework to allow further improvement.

2.4 Identification of Research Gap

There exist sustainability challenges in the Malaysian palm oil production, specifically in the upstream processes from plantation to crude palm oil production. There is, therefore, an urgent need to develop a holistic assessment framework to measure the real sustainability performance of palm oil production and to develop strategies to further improve the sustainability performance. The assessment framework should be inclusive, transparent, flexible, measurable and efficient in assessing sustainability performance, and provide a guideline for decision making and continuous improvement of the supply chain.

CHAPTER 3. METHODOLOGY

3.1 Objective

The objective of this chapter is to develop a holistic sustainability assessment framework for achieving environmental, economic and social sustainability objectives of crude palm oil production in Malaysia.

The methodology for assessing sustainability of crude palm oil production was developed in two stages.

Stage 1 – It involves the development of a sustainability assessment framework and demonstrates as to how different levels of indicators including PMs, KPIs and HPIs will be calculated to determine social, economic and environmental objectives of sustainability. Stage 1 of the methodology entitled "An Evaluation of Holistic Sustainability Assessment Framework for Palm Oil Production in Malaysia" was published in *Sustainability* journal (see **Appendix 2 – Paper 2**) (29).

Stage 2 – TBL indicators were first selected through a literature review and then they were finally selected by a consensus survey. The responses from the survey were used to determine the relevance of indicators and their level of importance. This stage of the framework was published in *Clean Technology and Environmental Policy* as an article entitled "Development of triple bottom line indicators for sustainability assessment framework of Malaysian palm oil industry" (see **Appendix 3-Paper 3)** (30).

3.2 Development of the Initial Theoretical Framework

Firstly, a review on the sustainability assessment concepts, TBL matrices, framework structures and tools, was carried out to come up with a suitable framework for palm oil sustainability assessment. Secondly, rigorous literature review was carried out to determine the initial set of TBL or sustainability assessment indicators and their ranking criteria for crude palm oil sustainability assessment. Thirdly, the formulae that were used to calculate indicators and the overall sustainability performance were discussed. Finally, the framework was tested using hypothetical data collected from literature and other published databases to identify opportunities for further improvement.

Figure 3.1 shows the steps for developing the framework for Palm Oil Sustainability Assessment (POSA).

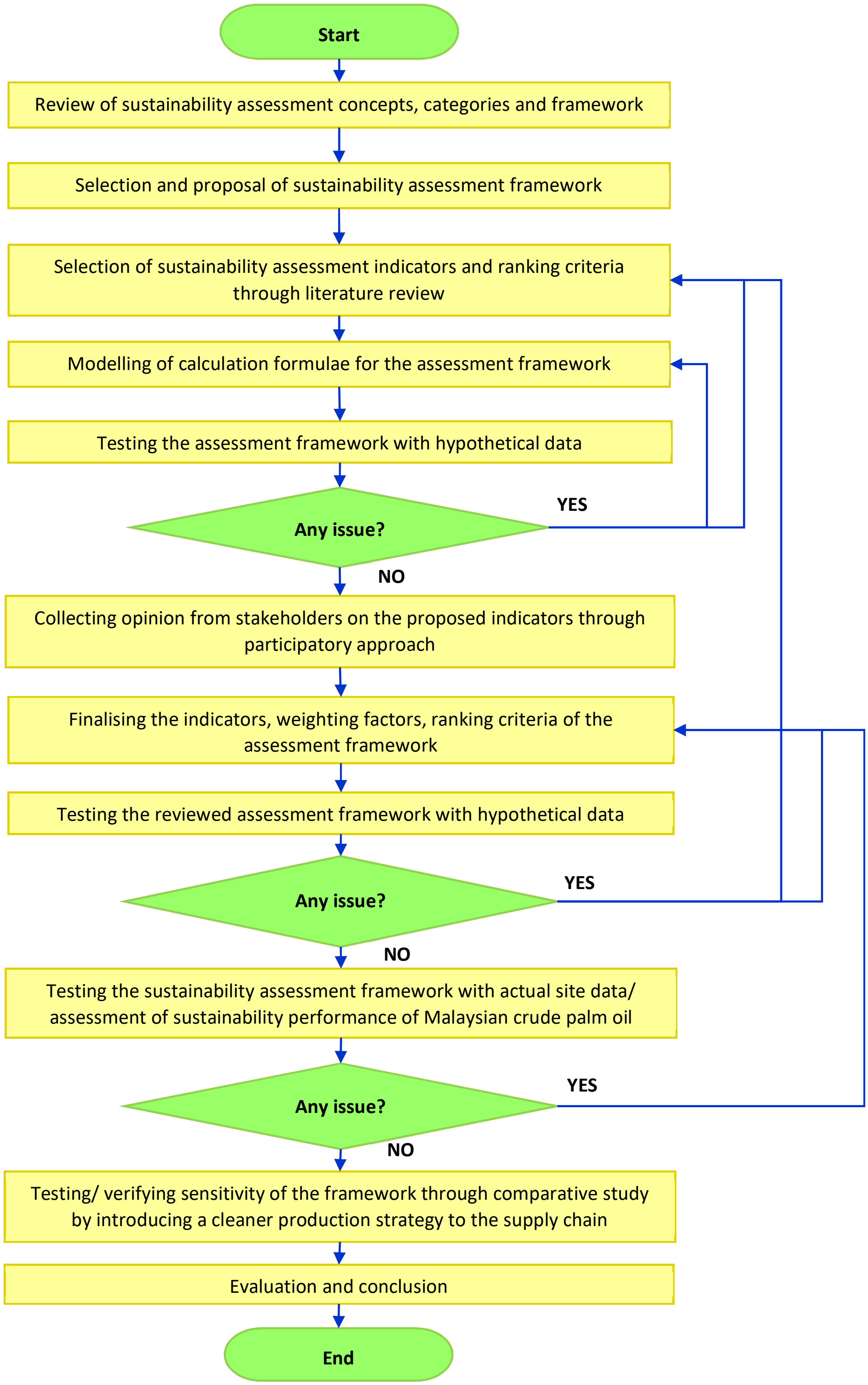

Figure 3.1: Theoretical Framework Development Flow Chart

Firstly, *underlying principles* of various sustainability assessment methods including LCA, Environmental Impact Assessment (EIA), as well as approach of IISD (38), Berkel (39), Federal Office for Spatial Planning of Switzerland (40), Devuyst (41), Biswas and Cooling (42) and Kucukvar (43) used for different applications were reviewed. These sustainability assessment approaches were built upon either strong or weak sustainability principle. Weak sustainability allows the trade-offs between three pillars of sustainability, which could favour some dominant economic agendas. Contradictory, strong sustainability considers both social and economic development to happen within the earth carrying capacity to produce products or services to meet the human needs and thus it prioritises the conservation of natural capital. This PhD research is based on the strong sustainability principle in order to address weaknesses of existing sustainability assessment methods and to enhance the socio-economic relationship between human wellbeing and eco-system services.

Different *types of sustainability assessment methods* including indicators/ indices, product-based assessment and integrated resource assessment were evaluated in Section 2.2.2 of Paper 2 (29). Pros and cons of each approach were critically reviewed before an integrated assessment model using multi-criteria analysis with a hierarchical indicator infrastructure was selected. This model enables the incorporation of all dimensions of TBL aspects (i.e. environmental, social and economic sustainability) of crude palm oil production for quantitative measurement in order to address the weaknesses of existing methods.

In Section 2.2.3 of the paper (29), circular, triangle and network structures for sustainability assessment were reviewed. A triangular structure was selected as it offers complex assessment involving different levels of aggregation with a wide range of indicators. It also shows the effects of each indicator (i.e. PM) on the assessment criteria (i.e. KPI) and dimensions (i.e. HPI). Figure 3.2 shows the POSA framework that follows this integrated approach.

In this framework, the overall sustainability assessment was segregated into three sustainability objectives i.e. Environment, Economy and Social. Each TBL objective consists of a number of headline performance indicators (HPIs), which form the highest aggregation level for the performance measurement against sustainability objectives. Each HPI is the aggregation of key performance indicators (KPIs), which further describe key impact areas of each HPI for palm oil production. The performance measures (PMs), which are the lowest level of aggregation, are established to provide quantitative values that could either directly or indirectly affect both KPIs and HPIs.

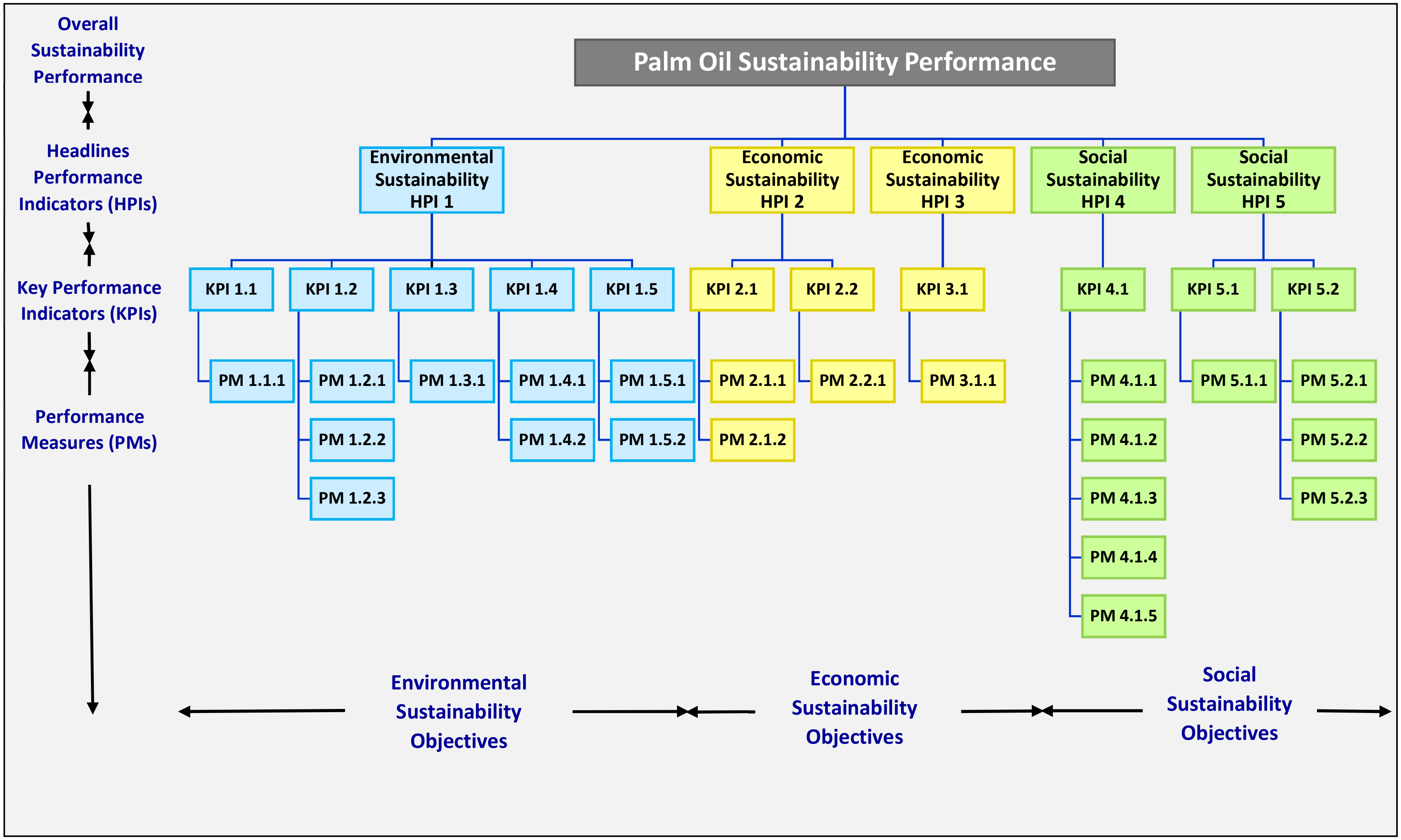

Figure 3.2: The initial framework of POSA (29)

Finally, Section 2.4 of Paper 2 (29) proposed the initial set of HPIs, KPIs and PMs to achieve Environment, Economic and Social sustainability objectives using the framework based on findings from literature review (Figure 3.2). In this framework, the PMs are assessed using a Likert scale of 1 – 5, where level 1, 3 and 5 represent the poorest, threshold and ideal performance, respectively. The criteria for ranking and threshold value of indicators were based on literature review (Section 3.1 of the paper). The complete list of HPI, KPI, PM and ranking criteria of the initial version of POSA framework was presented in Tables 1, 2 and 3 of paper 2. Following formulae were used for calculating KPI, HPI and overall sustainability performance (29).

- The performance of a KPI = the average of ranking value of PMs related to the KPI.

$$\textbf{Performance of KPI i.j} = \frac{\sum_{n=1}^{n=N} \textbf{PMi.j.n}}{\textbf{N}} \qquad \textbf{Equation 3.1}$$

where *PM i.j.n refers to n^{th} PM for KPI i.j for HPI i, and n = 1, 2, 3, …N; N = total number of PMs*

- Performance of an HPI = average performance of KPIs under this HPI.

$$\textbf{Performance of HPI i} = \frac{\sum_{j=1}^{j=J} \textbf{KPI i.j}}{\textbf{J}} \qquad \textbf{Equation 3.2}$$

where *KPI i.j refers to j^{th} KPI for HPI i, and j = 1,2,3, …, J; J = total number of KPI*

- Performance of each TBL sustainability objective = the average of ranking values of HPIs under this objective.

$$\textbf{Performance of TBL objective} = \frac{\sum_{i=1}^{i=I} \textbf{HPI i}}{\textbf{I}} \qquad \textbf{Equation 3.3}$$

where, *HPI i refers to i type of HPI for each TBL sustainability objective, I = 1, 2. …I; I = total number of HPI*

- Overall sustainability performance = the average performance of TBL objectives

$$\textbf{Overall Sustainability Performance} = \frac{\sum \textbf{TBL objectives}}{\textbf{3}} \qquad \textbf{Equation 3.4}$$

where, *TBL objectives refer to ranking values of environment, economic and social sustainability objectives*

The national statistics of year 2014-2015 and relevant literature provided secondary data to test the initial framework (Section 4 of Paper 2). Whilst this framework addressed the existing research gaps by quantifying TBL objectives of Malaysian crude palm oil production (Section 5 – Discussion of the paper), some weaknesses were identified as follows: -

- As the Likert scale was equally applied to all PMs, the relative importance of PMs was not captured while estimating the overall sustainability score. For example, the employment opportunity for the local people was an important hotspot, but it did not influence the overall sustainability performance as the remaining PMs which are relatively less important performed well.
- TBL objectives did not have equal number of PMs (*i.e.*, nine for environment, four for economy and nine for social objectives), Therefore the objective with fewer PMs (i.e. 4 PMs for economic objective as opposed to 9 PMs for environmental objective) had more weight on each of its PM. It means that the poor score or performance of a PM under the economic sustainability objective will highly influence the score of corresponding KPI, HPI, and the overall sustainability, compared to performance measures under environmental and social sustainability objectives.
- Threshold values for some PMs (e.g., "1.5.1 Fresh water consumption intensity—Water Footprint" and "1.5.2 Fossil fuel consumption intensity (Output/Input energy ratio)") that were based on average/ best industrial practices, might still be too high for the natural system, e.g., groundwater replenishment, fossil fuel resources, to accommodate the impact. The use of these threshold values of these PMs could overestimate environmental performance. Thus, these threshold values need to be made stringent in order to estimate the environmental PMs more accurately. This way, it will help materialise the concept of strong sustainability, as it gives priority to ecologically focused development.

It was thus recommended that weights need to be given to PMs in order to consider their relative importance. Alternatively, an equal number of PMs need to be developed for each of these three sustainability objectives. Besides, a thorough literature review needs to be carried out to select threshold values that are considered ecologically and socially sustainable for each PM.

3.3 Development of the TBL Indicators Using Participatory Approach

Aforementioned strategies were considered to address the weaknesses of the initial framework. The revised framework was developed and a journal entitled "Development of triple bottom line indicators for sustainability assessment framework of Malaysian palm oil industry" was published in *Clean Technologies and Environmental Policy* (**Appendix 3 – Paper 3**) (30).

Since performance measures play an important role to maintain the accuracy of measuring TBL objectives, the relevance and importance of these PMs were ascertained through a consensus conference/ participatory approach. This participatory approach involved the engagement of stakeholders at the early stage of the development of the framework to allocate appropriate weights to these indicators. These collaborative efforts would prevent conflict at the later stage of the implementation of framework, and create sustainable values for the stakeholders, as it was also explained by Badurdeen and Jawahir (44).

Firstly, a questionnaire was designed to gather stakeholders' opinions on the *relevance* and the *importance* of the initial set of 22 TBL PMs in assessing the sustainability of crude palm oil production in Malaysia. The questionnaire also had a provision for the participants to suggest additional indicators as well as to comment on the level of importance of these suggested PMs. Secondly, four categories of respondents from government, industry, academia, non-government organisations/local smallholders who are directly/ indirectly involved, or affected by activities associated with the production of crude palm oil, and also subject matter experts, were selected. Thirdly, different modes of surveys (online survey and hardcopy survey forms) were conducted using the same questionnaire to allow participants of diverse backgrounds with and without the access to the internet to participate in the survey. The Curtin Ethics Approval was obtained prior to this survey. Fourthly, data was collected from participants through online and hardcopy survey. The level of agreement from these stakeholders on the relevance and importance of the proposed PMs were compiled (Table 4 of Paper 3). Fifthly, additional feedback from the participants, including of the suggestions for new PM indicators were compiled for evaluation and consideration. Sixthly, the final selection of indicators was based on following criteria:

(1) the PMs received votes as 'relevant' and 'important' by more than 50% of the participants; and

(2) these PMs were proposed by at least 25% of the participants.

The weight of each PM was calculated using following equations.

Weight of each PM was calculated using Eq. 4.

$$\mathbf{W_j = n_{j1} * 1 + n_{j2} * 2 + n_{j3} * 3 + n_{j4} * 4 + n_{j5} * 5} \qquad \textbf{Equation 3.5}$$

where, j = 1, 2, 3, …………….M, is the performance measure (PM)

n_{j1} = Number of 'no responses' for PM of j,

n_{j2} = Number of 'least important' responses for PM of j,

n_{j3} = Number of 'less important' responses for PM of j,

n_{j4} = Number of 'important' responses for PM of j,

n_{j5} = Number of 'most important' responses for PM of j,

Total weight for M number of PMs has been calculated as follows:

$$\mathbf{W_{Total} = \sum_{j=1}^{M} W_j} \qquad \textbf{Equation 3.6}$$

The normalized weight (W'_j) for each PM has been calculated as follows:

$$\mathbf{W'_j} = \frac{\mathbf{W_j}}{\mathbf{W_{Total}}}$$ **Equation 3.7**

Selection of threshold values for PMs:

In Paper 3, threshold value was redefined as the targeted sustainability performance, and the assessment framework would measure how close the existing situation of palm oil production to threshold values to achieve sustainability. Hence, instead of ranking the PM performance from 1 – 5 with 3 as a threshold value in the initial framework (Paper 2), the revised approach ranked the PM performance from 1 – 5 where level 5 is considered as a threshold value/ expected performance. The sustainability gap would be the difference between the rank of a PM and 5.

The final version of the POSA framework, consisting of HPI, KPI and PM indicators, weights as well as the ranking criteria for each PM are presented in Table 1 and 2. Finally, the revised POSA framework was tested using the hypothetical data, most of which came from Paper 2 and some new data were obtained from literature (i.e. Step 7 of Paper 3)(30). Table 1 shows that there are 9, 7 and 6 PMs for environmental, social and economic objectives in the POSA framework. This shows that a strong sustainability was considered by giving environmental and social objectives more emphasis than economic objective. Also, natural capital conservation and social equity have more weight (40.47% and 31.83%) than the economic growth (27.70%).

Subsequently, the POSA framework was tested on the ground to measure the sustainability performance of the Malaysian crude palm oil production, and then the framework was further tested to assess its flexibility to changes in the supply chain in terms of incorporation of improvement strategies into the supply chain. The site-specific application of POSA and the sustainability outcomes were discussed in **Chapter 4 and 5.**

Table 1: The Finalised POSA Framework(30)

Sust. Obj		Headline Performance Indicator		Key Performance Indicator		Performance Measures	Overall Weight for PM
Env.	1	Natural Capital Conservation	1.1	Climate Change	1.1.1	GHG Emission	0.0450
			1.2	Air, Water and Soil Quality	1.2.1	NOx emission intensity from palm oil mill	0.0393
					1.2.2	Biological Oxygen Demand of water discharged from POME pond	0.0447
					1.2.3	Soil Nitrate Level measured through pH in waterway	0.0444
			1.3	Waste Generation	1.3.1	% biomass recovery/ recycling	0.0450
			1.4	Biodiversity	1.4.1	Plantation Practice	0.0463
					1.4.2	Land Use	0.0447
					1.4.3	Species Loss	0.0538
			1.5	Resources Consumption	1.5.1	Fossil fuel consumption intensity (Output/Input energy ratio)	0.0415
Eco.	2	Business Continuity and Resiliency	2.1	Productivity efficiency	2.1.1	Plantation yield	0.0476
					2.1.2	Mill production efficiency	0.0485
			2.2	Consistent Profitability	2.2.1	Actual Growth Rate	0.0447
	3	Sharing of Economic Power	3.1	Relative Poverty	3.1.1	Average annual income per worker	0.0452
			3.2	Local community inclusion and distribution of wealth	3.2.1	Employment opportunity for the local	0.0471
					3.2.2	Smallholders' equity	0.0439
Soc.	4	Social Wellbeing	4.1	Meeting Essential Human Needs	4.1.2	Workers' accessibility to water supply	0.0471
					4.1.3	Workers' accessibility to health care	0.0476
					4.1.4	Provision of sanitation facilities to workers	0.0474
					4.1.5	Provision of housing facilities to workers	0.0460
	5	Social Equity	5.1	Local community empowerment and engagement	5.1.1	Access to information and knowledge	0.0425
					5.1.2	Fair partnership and community involvement in decision making.	0.0433
					5.1.3	Level of community acceptance to plantation and mill activities	0.0444

Table 2: Revised Performance Measures and Ranking Criteria(30)

Performance Measures		Ranking Criteria	
1.1.1	GHG Emission	1	> 1 tCO2eq/tonne CPO
		2	> 0.8 tCO2eq/tonne CPO
		3	0.5 - 0.8 tCO2eq/tonne CPO
		4	< 0.50 tCO2eq/tonne CPO
		5	< 0.15 tCO2eq/tonne CPO
1.2.1	NOx emission intensity from palm oil mill	1	>500 mg/m3 emission (continuous)
		2	>450 mg/m3 emission (continuous)
		3	>400 mg/m3 emission (continuous)
		4	>350 mg/m3 emission (continuous)
		5	<350 mg/m3 emission (continuous)
1.2.2	Biological Oxygen Demand of water discharged from POME pond	1	>250 mg/l (3 days, 30 degC)
		2	>200 mg/l (3 days, 30 degC)
		3	>150 mg/l (3 days, 30 degC)
		4	>100 mg/l (3 days, 30 degC)
		5	<100 mg/l (3 days, 30 degC)
1.2.3	Soil Nitrate Level measured through pH in waterway	1	Total nitrogen >400mg/l
		2	Total nitrogen >350mg/l
		3	Total nitrogen >300mg/l
		4	Total nitrogen >250mg/l
		5	Total nitrogen <200mg/l
1.3.1	% biomass recovery/ recycling	1	<25% recovery
		2	>25% recovery
		3	>50% recovery
		4	>75% recovery
		5	100% recovery
1.4.1	Plantation Practice	1	Meet <3 of the plantation practice requirements
		2	Meet 3/6 plantation practice requirement
		3	Meet 4/6 plantation practice requirements
		4	Meet 5/6 plantation practice requirements
		5	Meet all the plantation practice requirements
1.4.2	Land Use	1	Planted on Peat Land/ HCVF
		2	Planted on secondary forest/ replaced other crops
		3	Replanting on agricultural land
		4	Replanting with Best Management Practice
		5	Replanting with agricultural intensification
1.4.3	Species Loss	1	Majority of the locals agree that there is a serious species loss due to palm oil development and there is no conservation effort at all.
		2	Majority of the locals agree that there is a significant species loss due to palm oil development and there are little conservation efforts seen.
		3	Majority of the locals agree that there are some species loss due to palm oil development and there are little conservation efforts seen.
		4	Majority of the locals agree that there are some species loss due to palm oil development although significant conservation efforts are put in.
		5	Majority of the locals agree that there is no species loss due to palm oil development and there are proactive programmes for conservation.
1.5.2	Fossil fuel consumption intensity (Output/Input energy ratio)	1	<6
		2	<7
		3	<8
		4	<9
		5	>=9
2.1.1	Plantation yield	1	<16 tonne per ha per year
		2	<17 tonne per ha per year
		3	<18 tonne per ha per year
		4	<19 tonne per ha per year
		5	>=19 tonne per ha per year
2.1.2	Mill production efficiency	1	<0.18 tonne CPO per tonne FFB
		2	<0.19tonne CPO per tonne FFB
		3	<0.20 tonne CPO per tonne FFB
		4	<0.21tonne CPO per tonne FFB
		5	>=0.21 tonne CPO per tonne FFB

2.2.1	Actual Growth Rate	1	>15% deviation from Sustainable Growth Rate
		2	15% deviation from Sustainable Growth Rate
		3	10% deviation from Sustainable Growth Rate
		4	5% deviation from Sustainable Growth Rate
		5	0% deviation from Sustainable Growth Rate
3.1.1	Average annual income per worker	1	<20% of national median income
		2	<30% of national median income
		3	<40% of national median income
		4	<50% of national median income
		5	>=50% of national median income
3.2.1	Employment opportunity for the local	1	<25% local employment
		2	>=25% local employment
		3	>50% local employment
		4	>75% local employment
		5	100% local employment
3.2.2	Smallholders' equity	1	<10% of CPO sourced from smallholders
		2	<20% of CPO sourced from smallholders
		3	<30% of CPO sourced from smallholders
		4	<50% of CPO sourced from smallholders
		5	>=50% of CPO sourced from smallholders
4.1.1	Workers' accessibility to water supply	1	< 25% accessible to portable water
		2	> 25% accessible to portable water
		3	> 50% accessible to portable water
		4	> 75% accessible to portable water
		5	100% accessible to portable water
4.1.2	Workers' accessibility to health care	1	< 25% accessible to healthcare facilities
		2	> 25% accessible to healthcare facilities
		3	> 50% accessible to healthcare facilities
		4	> 75% accessible to healthcare facilities
		5	100% accessible to healthcare facilities
4.1.3	Provision of sanitation facilities to workers	1	< 25% accessible to sanitation facilities
		2	> 25% accessible to sanitation facilities
		3	> 50% accessible to sanitation facilities
		4	> 75% accessible to sanitation facilities
		5	100% accessible to sanitation facilities
4.1.4	Provision of housing facilities to workers	1	< 25% provision to housing facilities
		2	> 25% provision to housing facilities
		3	> 50% provision to housing facilities
		4	> 75% provision to housing facilities
		5	100% provision to housing facilities
5.1.1	Sharing of information with the local community	1	No information available
		2	Information available but local community are not informed
		3	Local community informed prior to the plantation and mill development
		4	Local community informed periodically on the plantation and mill development
		5	Local community are timely updated
5.1.2	Fair Partnership and Community involvement in decision making	1	No involvement at all in decision making/ No prior consultation of land use
		2	Indirect communication channels are available/ No prior consent of land use.
		3	Local community could provide feedback to plantation owner/ mill management through establish channel on any issues affecting them, and there is free, prior and informed consent (FPIC) in using the land.
		4	Local community has representation in plantation/ mill HSE Committee, FPIC is available with considerations offered to the local people.
		5	FPIC is treated as mandatory in any activities, legally binding land agreement is available.
5.1.3	Level of community acceptance to plantation and mill activities	1	< 20% agreement from community
		2	< 30% agreement from community
		3	< 40% agreement from community
		4	< 50% agreement from community
		5	> 50% agreement from community

CHAPTER 4. SUSTAINABILITY ASSESSMENT ON THE MALAYSIAN CRUDE PALM OIL

4.1 Objective

The objective of this chapter is to assess the application of POSA framework on the ground. A common Malaysian crude palm oil supply chain has thus been selected in the Sarawak State of Borneo Island to apply this framework for sustainability assessment.

This chapter was published as a journal article entitled "Sustainability assessment for crude palm oil production in Malaysia using the palm oil sustainability assessment framework" in the journal of *Sustainable Development* (see **Appendix 4 – Paper 4**) (31)

4.2 Goal, Scope and System Boundary of the Assessment

Section 2.1 of Paper 4 described the goal, scope and system boundary of the crude palm oil supply chain for sustainability assessment. The assessment was conducted to measure sustainability performance of crude palm oil production in Malaysia and to identify TBL hotspots in the supply chain for developing sustainability improvement strategies. The system boundary of this assessment considered all processes in the supply chain, including seedling production at the nursery, fresh fruit bunches (FFB) production in various scales of plantation and crude palm oil production at the palm oil mill (Figure 4.1). A functional unit of 1 tonne of crude palm oil production was considered, meaning that the denominator of TBL PMs is per tonne of crude palm oil production. All PMs were calculated for 1 tonne of crude palm oil production.

4.3 Supply Chain Selection

Following list of selection criteria were considered for supply chain selection:

- location of the supply chain, where most Malaysian's oil palm trees are grown,
- types of soil suitable for oil palm trees plantation,
- types of plantations (e.g. large-scale or smallholders' plantations) that are commonly used as a source for Fresh Fruit Bunches (FFB),
- types of technology/ processes used by most of the crude palm oil mills in Malaysia.

Following the aforementioned selection criteria, the case study supply chain was finally selected in Borneo Island of Malaysia, which sourced its FFB from both large and small plantations and seeding was sourced from the nursery licenced by Malaysian Palm Oil Board (MPOB) , and oil palm trees were planted on mineral soil in both large and small plantations, and the FFB was milled in a typical palm oil mill without any biogas plant/ trapping system.

4.4 Data Collection for the POSA assessment

Site-specific data were collected to determine the ranks of 22 PMs of the POSA framework. Eighteen out of these 22 PMs were ranked based on the quantitative data obtained from the field survey, while the other 4 PMs (i.e. species loss, sharing of information with the local community, fair partnership and community involvement in decision making, level of community acceptance to plantation and mill activities) required collective feedback from the local people. In this case, 41 representatives from 85 villages were interviewed to obtain collective feedback, which was used to rank these PMs. Therefore, two sets of questionnaires were developed, of which one was designed to collect the primary data needed to calculate PMs, and the other one consisted of multiple-choice questions in order to know the level of expectation to determine the ranking of four qualitative PMs (Section 2.3 of Paper 4).

The industries along the supply chain including nursery, large and small plantations, palm oil mills, and local people were engaged in the data collection process. The data collection process and assumptions considered were discussed in detail in Section 2.4 of Paper 4. Primary data collected was later processed to calculate actual performance of each PM. The performance of each PM was compared against the pre-determined ranking criteria of POSA framework in order to determine their position or score on a Likert scale (Section 2.5 of Paper 5).

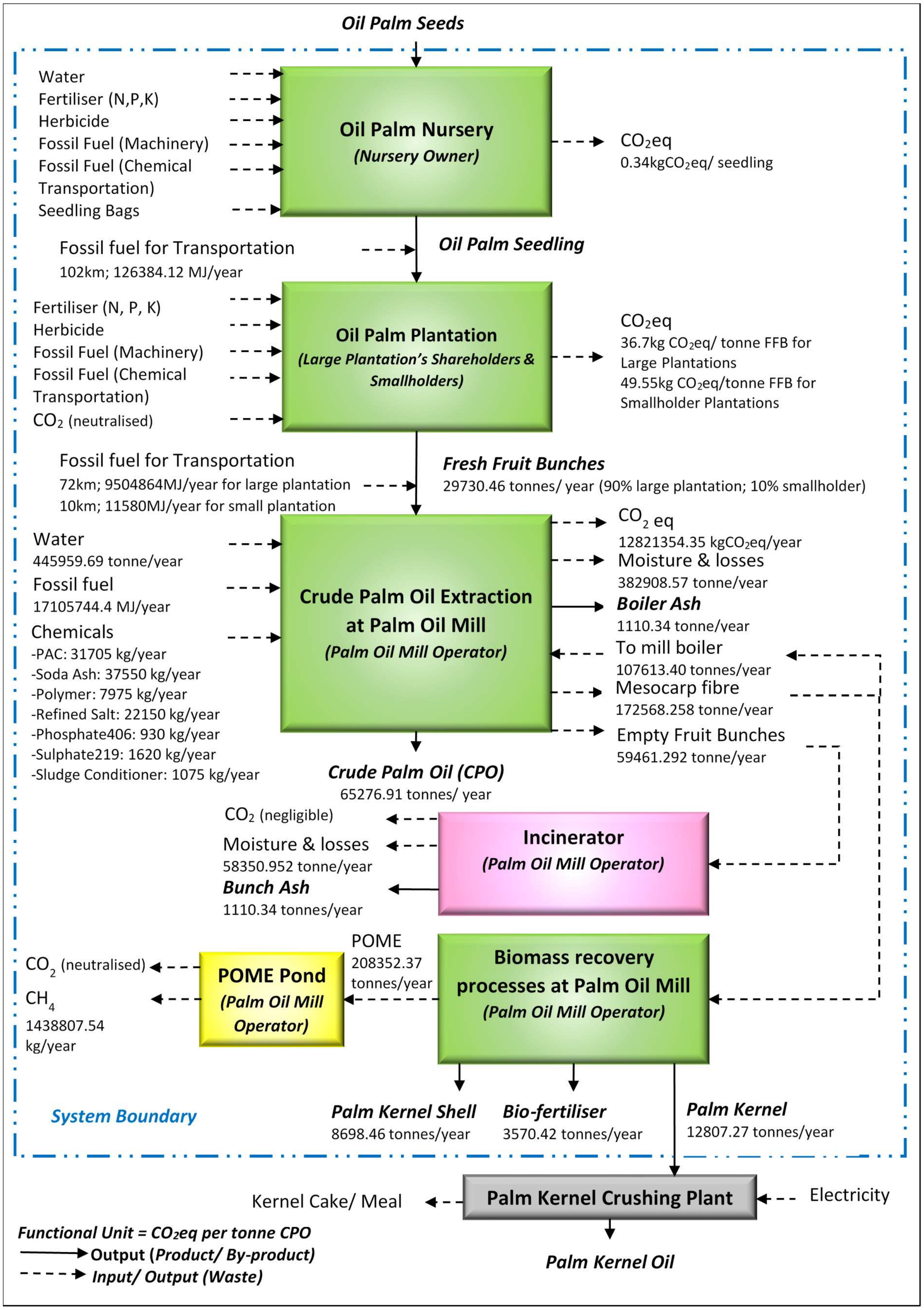

Figure 4.1: System Boundary of the Assessment (31)

4.5 Results and Finding

Figure 4.2 shows the gap (-1.53) that needs to be overcome in order to achieve the overall sustainability performance of the most common crude palm oil supply chain in Malaysia. The overall sustainability score of this crude palm oil supply chain was estimated to be 3.47/5, which is below the sustainability target of 5/5. The TBL implications were discussed in detail in Section 3.1 of Paper 4. This gap was resulted from the poor performance of some indicators, including smallholder's equity, GHG emission, percentage of biomass waste recovery, plantation practice, average income per worker and employment opportunity for the local people. There exists large gaps between rank and the threshold values of these PMs. These PMs were thus considered as 'sustainability hotspots', where improvements were required to increase the overall sustainability scores of the crude palm oil supply chain. These hotspots were evaluated, and a number of sustainability improvement strategies were proposed for each of these PMs through a thorough literature review (Table 3 of Paper 4). For example, the improvement strategies that were considered for GHG emission could be the installation of a biogas trapping system, increased biomass recovery, reduction of energy intensity by using more efficient machinery; introduction of agricultural intensification (e.g. land sparing) were considered to improve the performance of plantation practice, land use and species loss. The engagement with the local smallholders, could be strengthen by sourcing more local FFB (i.e. PMs of smallholder equity), by increasing the actual growth rate of the supply chain, and by information sharing, communication and fair partnership with the local community.

The application of POSA framework on the ground concluded that the assessment has a great potential to be accepted and adopted by the industries. The ranking criteria was found to work in an actual site condition as the calculated value was comparable to the ranking criteria (e.g. plantation yield and mill production efficiency). The sustainability gaps and hotspots could be clearly identified at different levels of indicators, showing avenues for improvement within the supply chain to achieve triple bottom line sustainability objectives. Despite excellent performance of HPI of business continuity and resiliency, the economic sustainability objective was found to have a large gap to achieve threshold (-1.87), due to the poor performance of another HPI for sharing of economic power (-3.24). The poor performance of this HPI could be tracked down by investigating into KPI and PM levels. There exists large sustainability gaps for KPIs for relative poverty (-3.00) and local community inclusion and distribution of wealth (-3.48), as the PMs for these KPIs i.e. average annual income per worker, employment opportunity for the local and smallholders' equity have large gaps between threshold and ranking values (between -3 and -4) (Table 3). The framework was proved to be a useful decision-making tool to further improve sustainability performance of crude palm oil production.

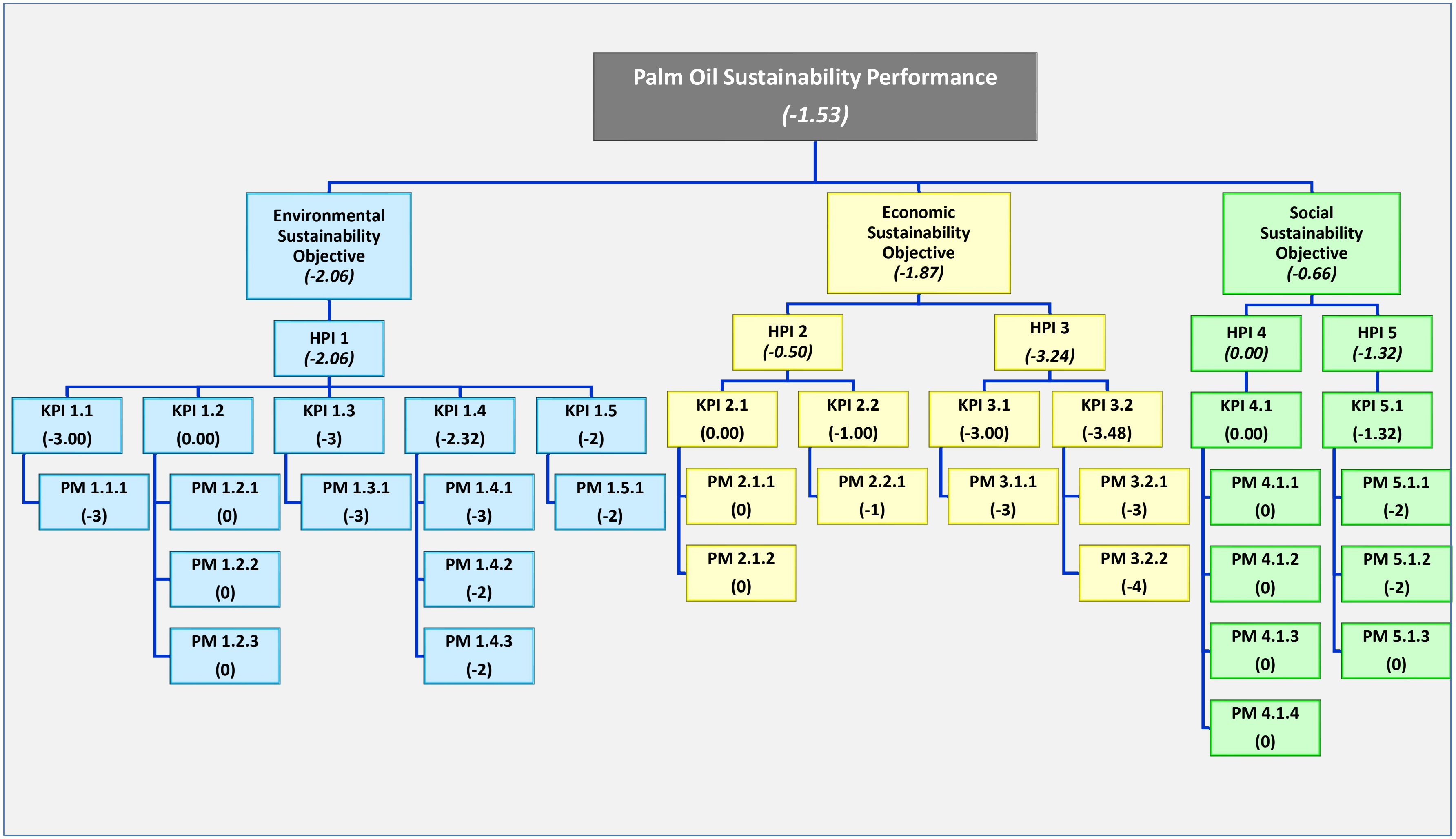

Figure 4.2: Gap to Sustainability at Different Level for Crude Palm Oil Supply Chain

Table 3: Results of Sustainability Assessment for the Most Common Crude Palm Oil Supply Chain in Malaysia (Gap Analysis) (31)

Sustainability Objectives	Headline Performance Indicator	Key Performance Indicator	Performance Measures	Ranking value for PM	Gap to threshold	Overall Weight for PM	Score for KPI	Score for HPI	Score for Sustainability Objective	Score for Overall Sustainability
Environment	1 Natural Capital Conservation	1.1 Climate Change	1.1.1 GHG Emission	2	-3	0.0450	-3.00	-2.06	**-2.06**	**-1.53**
		1.2 Air, Water and Soil Quality	1.2.1 NOx emission intensity from palm oil mill	5	0	0.0393	0.00			
			1.2.2 BOD of water discharged from POME pond	5	0	0.0447				
			1.2.3 Soil Nitrate Level measured through pH in waterway	5	0	0.0444				
		1.3 Waste Generation	1.3.1 % biomass recovery/ recycling	4	-1	0.0450	-3.00			
		1.4 Biodiversity	1.4.1 Plantation Practice	2	-3	0.0463	-2.32			
			1.4.2 Land Use	3	-2	0.0447				
			1.4.3 Species Loss	3	-2	0.0538				
		1.5 Resources Consumption	1.5.1 Energy (Fossil fuel and biomass) consumption intensity (Output/Input energy ratio)	1	-4	0.0415	-2.00			
Economy	2 Business Continuity and Resiliency	2.1 Productivity efficiency	2.1.1 Plantation yield	5	0	0.0476	0.00	-0.50	**-1.87**	
			2.1.2 Mill production efficiency	5	0	0.0485				
		2.2 Consistent Profitability	2.2.1 Actual Growth Rate	4	-1	0.0447	-1.00			
	3 Sharing of Economic Power	3.1 Relative Poverty	3.1.1 Average annual income per worker	2	-3	0.0452	-3.00	-3.24		
		3.2 Local community inclusion and distribution of wealth	3.2.1 Employment opportunity for the local	2	-3	0.0471	-3.48			
			3.2.2 Smallholders' equity	1	-4	0.0439				
Social	4 Social Wellbeing	4.1 Meeting Essential Human Needs	4.1.1 Workers' accessibility to water supply	5	0	0.0471	0.00	0.00	**-0.66**	
			4.1.2 Workers' accessibility to health care	5	0	0.0476				
			4.1.3 Provision of sanitation facilities to workers	5	0	0.0474				
			4.1.4 Provision of housing facilities to workers	5	0	0.0460				
	5 Social Equity	5.1 Local community empowerment and engagement	5.1.1 Sharing of information with the local community	3	-2	0.0425	-1.32	-1.32		
			5.1.2 Fair partnership and community involvement in decision making.	3	-2	0.0433				
			5.1.3 Level of community acceptance to plantation and mill activities	5	0	0.0444				

CHAPTER 5. COMPARATIVE ASSESSMENT

5.1 Objective

The objective of this chapter is to investigate the sustainability implications of the application of improvement strategies to crude palm oil supply chain in Malaysia.

This chapter was published as an article entitled "Sustainability Implications of the Incorporation of a Biogas Trapping System into a Conventional Crude Palm Oil Supply Chain" in *Sustainability* journal (see **Appendix 5 – Paper 5**) (32).

5.2 Objectives of the Comparative Study

In Chapter 4, biogas trapping system was considered as one of the sustainability improvement strategies in order to reduce the GHG emission of the supply chain. A comparative study was carried out between existing and improved crude palm oil supply chains to achieve following specific objectives:

- To evaluate the TBL implications of the incorporation of sustainability improvement strategy (i.e. a biogas trapping system on the overall sustainability performance of crude palm oil production).
- To assess the flexibility of the POSA framework in terms of its response to the changes in the supply chain due to technological improvement.

5.3 Incorporating Biogas Trapping System to the Crude Palm Oil Supply Chain

In this comparative study (Section 2 of Paper 5), site-specific data was collected from a KUBOTA biogas cum polishing plant (BGPP) (Figure 5.1). This plant replaces open-ponding POME treatment process in the baseline crude palm oil supply chain as discussed in Paper 4 (31) . The sustainability performance of this improved crude palm oil supply chain was then assessed using the POSA framework, and the results were compared against the baseline supply chain.

The KUBOTA BGPP was designed to convert POME from palm oil mill to biogas (with a methane content of 62.55%), for use as fuel by the neighbouring brick factory. The stages of BGPP, biogas plant, polishing plant and sludge pond, were included in the system boundary of the existing supply chain (Figure 5.2). The operation of brick factory using biogas was excluded as it did not contribute directly or indirectly to the crude palm oil production.

Figure 5.1: The KUBOTA biogas cum polishing plant

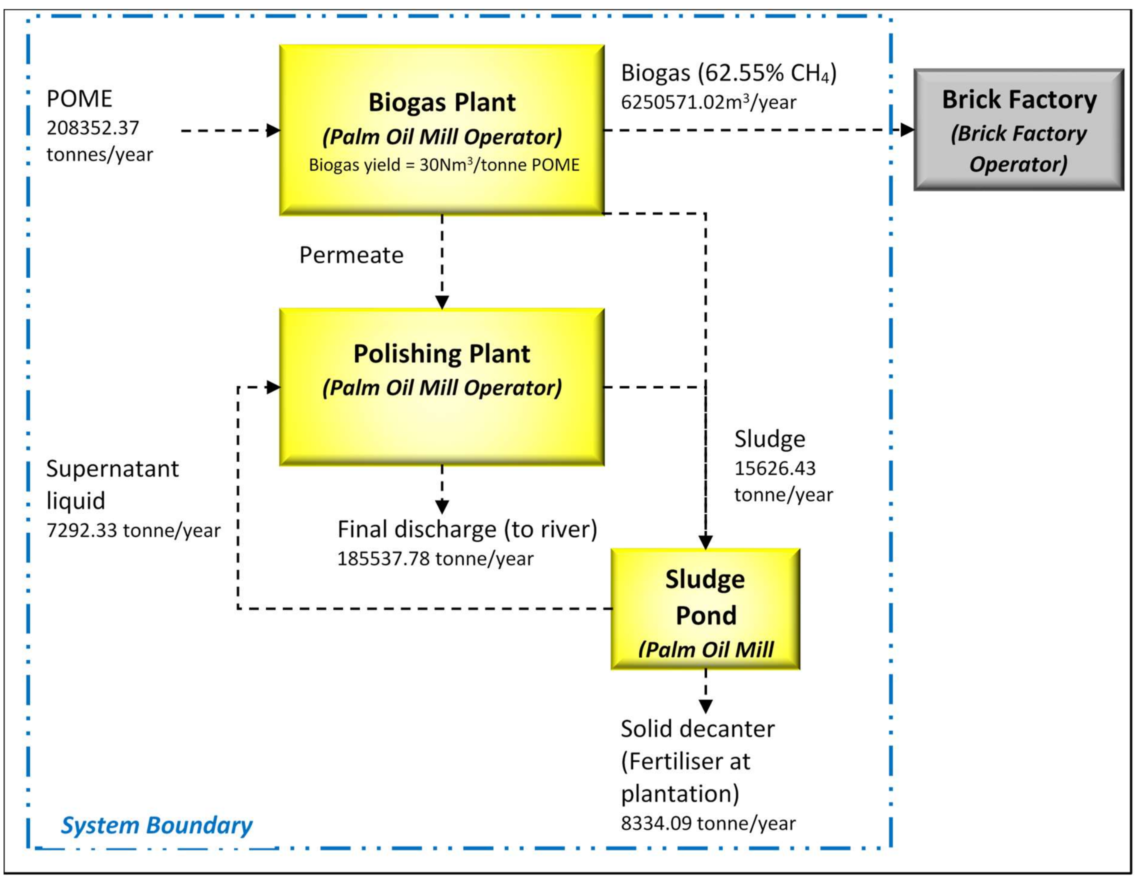

Figure 5.2: The KUBOTA biogas trapping system

5.4 POSA Assessment Results for the Comparative Supply Chain

Table 4 confirms that the incorporation of a biogas trapping system (32) had resulted in significant improvement in the sustainability performance of 4 Environmental and 1 Economic PMs. Firstly, the GHG emissions from the supply chain significantly reduced by 75.9% (from 0.814 to 0.196 $kgCO_2eq$ per tonne CPO) mainly due to the trapping of powerful GHG (i.e. CH_4) from POME. Secondly, biological oxygen demand or BOD of water discharged from POME ponds could be reduced to a level below 20 mg/L. Thirdly, this enclosed system eliminated the risks of surface water and groundwater pollutions by avoiding the overflow of POME in the event of a flood. Fourthly, the biomass waste recovery in palm oil supply chain increased from 82% to 99.99%. Lastly, the biogas generation could increase the total energy output from the crude palm oil supply chain by 4.6%, and so the output/input energy ratio increased from 2.45 to 2.56. About 7,233 tonnes equivalent of coal can potentially be conserved for the future generations due to the use of biogas further enhanced intergenerational social equity.

Whilst the incorporation of BGPP to the crude palm oil supply chain generated a profit of RM 4.04 million per year with a quick payback period of 2.87 years, the additional investment on this plant had caused a large gap between Actual Growth Rate (AGR) and the Sustainable Growth Rate (SGR). This large gap means that the business is underperforming. In order to reduce this gap, the SGR should be reduced by using available cash in hand more productively such as by increasing dividends of shareholders or by reducing the business debt levels. Alternatively, the AGR could be increased by increasing sales and production, through processing more FFB into CPO, palm kernel, and other by-products within the existing facilities.

This biogas trapping system could reduce the unpleasant odor by avoiding the use of an open pond treatment system and so this strategy is expected to improve the satisfaction and acceptance of the surrounding community towards the supply chain (PM 5.1.3).

Table 5 (32) compares PMs, KPIs, HPIs, sustainability objectives and overall sustainability assessment results of the baseline supply chain (i.e. within bracket in italic font) with those for the improved supply chain with BGPP (i.e. in bold). The overall sustainability performance improved from 3.47/5 to 3.59/5 due to the incorporation of this improvement strategy. The gap between calculated value and sustainability threshold was further analyzed with the aid of Figure 5.3. A significant improvement was observed in environmental HPI of natural capital conservation due to higher level of GHG emission reduction and increased waste recovery. Economic sustainability was slightly reduced from (3.13/5 to 2.88/5) due to lower score in HPI for business continuity and resiliency, resulting from a large deviation of AGR from SGR.

The introduction of BGPP is not enough to close the sustainability gap for the crude palm oil supply chain. The hotspots that remain to be treated are plantation practice, energy (fossil fuel and biomass) consumption intensity (Output/Input energy ratio), average annual income per worker, employment opportunity for the local people and smallholders' equity to further improve the overall sustainability performance.

Table 4: Comparison of performance measures of supply chains with and without the biogas trapping system.(32)

Sust. Obj.	Headline Performance Indicator (HPI)*		Key Performance Indicator (KPI)*		Performance Measures (PM)*		PM values without biogas trapping	PM values with Biogas trapping
Env.	1	Natural Capital Conservation	1.1	Climate Change	1.1.1	GHG Emission (kgCO_2eq per tonne CPO)	0.814	0.196
			1.2	Air, Water and Soil Quality	1.2.1	NOx emission intensity from palm oil mill	0	0
					1.2.2	Biological Oxygen Demand of water discharged from POME pond	22.25	17
					1.2.3	Soil Nitrate Level measured through pH in waterway	92	92
			1.3	Waste Generation	1.3.1	% biomass waste recovery/recycling	81.809%	≈100%
			1.4	Biodiversity	1.4.1	Plantation Practice (Number of best practices met)	3.5/6	3.5/6
					1.4.2	Land Use	Planted on formal agricultural land	Planted on formal agricultural land
					1.4.3	Species loss	12% voted 1, 5% voted 2, 39% voted 3, 34% voted 4, 10% voted 5	12% voted 1, 5% voted 2, 39% voted 3, 34% voted 4, 10% voted 5
			1.5	Resources Consumption	1.5.1	Energy (Fossil fuel and biomass) consumption intensity (Output/Input energy ratio)	2.45	2.56
Eco.	2	Business Continuity and Resiliency	2.1	Productivity efficiency	2.1.1	Plantation yield (tonne FFB/hectare)	25.55	25.55
					2.1.2	Mill production efficiency (tonne CPO per tonne FFB)	0.2196	0.2196
			2.2	Business Continuity	2.2.1	Actual Growth Rate (deviation from sustainable growth rate)	−4%	−7%
	3	Sharing of Economic Power	3.1	Relative Poverty	3.1.1	Average annual income per worker (% of national average income)	26.95	26.95
			3.2	Local community inclusion and distribution of wealth	3.2.1	Employment opportunity for the local (% of local employment)	31.33	31.33
					3.2.2	Smallholders' equity	10%	10%
Soc.	4	Social Wellbeing	4.1	Meeting Essential Human Needs	4.1.1	Workers' accessibility to water supply	100%	100%
					4.1.2	Workers' accessibility to health care	100%	100%
					4.1.3	Provision of sanitation facilities to workers	100%	100%
					4.1.4	Provision of housing facilities to workers	100%	100%
	5	Social Equity	5.1	Local community empowerment and engagement	5.1.1	Sharing of information with the local community	32% voted 1, 10% voted 2, 36% voted 3, 22% voted 4, 0% voted 5	32% voted 1, 10% voted 2, 36% voted 3, 22% voted 4, 0% voted 5
					5.1.2	Fair Partnership and Community involvement in decision making	19% voted 1, 20% voted 2, 29% voted 3, 27% voted 4, 5% voted 5	19% voted 1, 20% voted 2, 29% voted 3, 27% voted 4, 5% voted 5
					5.1.3	Level of community acceptance to plantation and mill activities	85% agreement	85% agreement

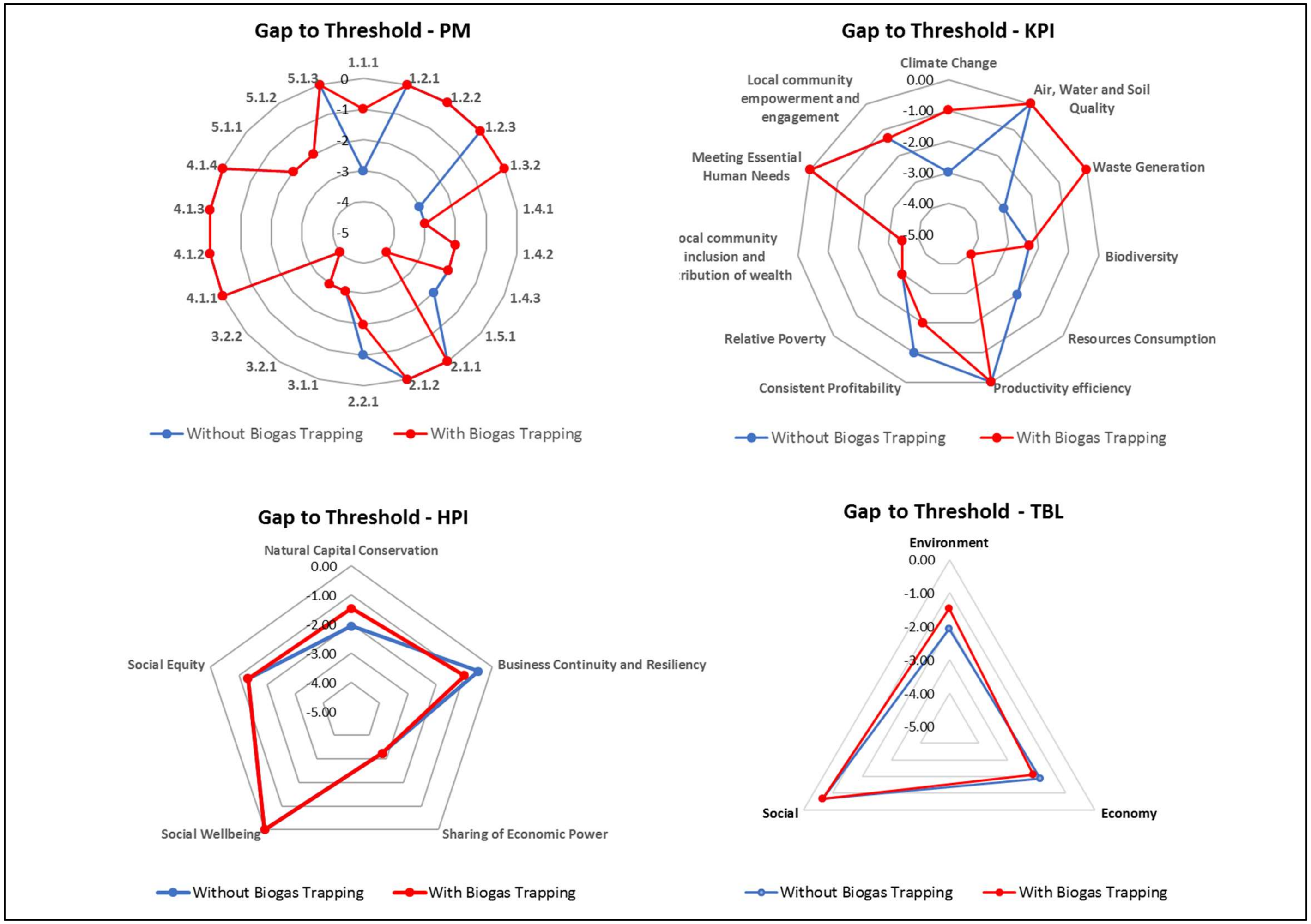

Figure 5.3: Gap to Threshold for PM, KPI, HPI and TBL Objective Before and After the Incorporation of Biogas Trapping System

Table 5: Sustainability assessment of crude palm oil supply chain with biogas trapping using POSA framework.(32)

Sust. Obj.		Headline Performance Indicator		Key Performance Indicator		Performance Measures	Ranking for PM	Overall Weight for PM	Score for KPI	Score for HPI	Score for Sust. Obj.	Score for Overall Sust.
Env.	1	Natural Capital Conservation	1.1	Climate Change	1.1.1	GHG Emission	**4** *(2)*	**0.045**	**4.00** *(2.00)*	**3.54** *(2.94)*	**3.54** *(2.94)*	*3.59 (3.47)*
			1.2	Air, Water and Soil Quality	1.2.1	NOx emission intensity from palm oil mill	**5** *(5)*	**0.0393**	**5.00** *(5.00)*			
					1.2.2	Biological Oxygen Demand of water discharged from POME pond	**5** *(5)*	**0.0447**				
					1.2.3	Soil Nitrate Level measured through pH in waterway	**5** *(5)*	**0.0444**				
			1.3	Waste Generation	1.3.1	% Biomass waste recovery/recycling	**5** *(4)*	**0.045**	**5.00** *(4.00)*			
			1.4	Biodiversity	1.4.1	Plantation Practice	**2** *(2)*	**0.0463**	**2.68** *(2.68)*			
					1.4.2	Land Use	**3** *(3)*	**0.0447**				
					1.4.3	Species loss	**3** *(3)*	**0.0538**				
			1.5	Resources Consumption	1.5.1	Energy (Fossil fuel and biomass) consumption intensity (Output/Input energy ratio)	**1** *(1)*	**0.0415**	**1.00** *(1.00)*			
Eco.	2	Business Continuity and Resiliency	2.1	Productivity efficiency	2.1.1	Plantation yield	**5** *(5)*	**0.0476**	**5.00** *(5.00)*	**4.00** *(4.50)*	**2.88** *(3.13)*	
					2.1.2	Mill production efficiency	**5** *(5)*	**0.0485**				
			2.2	Business Continuity	2.2.1	Actual Growth Rate	**3** *(4)*	**0.0447**	**3.00** *(4.00)*			
	3	Sharing of Economic Power	3.1	Relative Poverty	3.1.1	Average annual income per worker	**2** *(2)*	**0.0452**	**2.00** *(2.00)*	**1.76** *(1.76)*		
			3.2	Local community inclusion and distribution of wealth	3.2.1	Employment opportunity for the local	**2** *(2)*	**0.0471**	**1.52** *(1.52)*			
					3.2.2	Smallholders' equity	**1** *(1)*	**0.0439**				
Soc.	4	Social Wellbeing	4.1	Meeting Essential Human Needs	4.1.1	Workers' accessibility to water supply	**5** *(5)*	**0.0471**	**5.00** *(5.00)*	**5.00** *(5.00)*	**4.34** *(4.34)*	
					4.1.2	Workers' accessibility to health care	**5** *(5)*	**0.0476**				
					4.1.3	Provision of sanitation facilities to workers	**5** *(5)*	**0.0474**				
					4.1.4	Provision of housing facilities to workers	**5** *(5)*	**0.046**				
	5	Social Equity	5.1	Local community empowerment And engagement	5.1.1	Sharing of information with the local community	**3** *(3)*	**0.0425**	**3.68** *(3.68)*	**3.68** *(3.68)*		
					5.1.2	Fair Partnership and Community involvement in decision making	**3** *(3)*	**0.0433**				
					5.1.3	Level of community acceptance to plantation and mill activities	**5** *(5)*	**0.0444**				

5.5 Discussion on the Results of Comparative Study

Significant improvements are found in environmental sustainability due to the use of a biogas trapping system. Whilst the gap between the ranking and threshold values reduced for GHG emissions and waste recovery/ recycled PMs, biodiversity became the environmental hotspot, as the impact caused by upstream plantation activities in producing Fresh Fruit Bunches (FFB) for the supply chain remained unsolved. The supply chain thus needs to consider strategies in improving plantation practices (e.g. increase landscape heterogeneity, practice integrated farming, zero burning), reduce land use changes and the loss of biodiversity. Energy consumption (fossil fuel and biomass) intensity still remained as another hotspot despite additional amount of bioenergy was generated in BGPP. This is because the current calculation method considers all forms of energy inputs within the system boundary, including energy input that is recovered or generated from waste. For example, biomass waste including mesocarp fibre and empty fruit bunches which could otherwise be wasted, was recovered from the supply chain for combustion in a boiler to produce steam for the palm oil mill. This recovered amount of energy was added as an input to the system rather than as a substitute or avoidance of commercial energy. About 96.9% of the energy input of the palm oil mill came from biomass waste recovered from the supply chain. Thus, net energy input by subtracting the recovered energy from the total energy input could have been considered in calculating the PM for energy consumption intensity (i.e. input/ output ratio).

Incremental capital investment and operating cost, and additional income due to this biogas plant would change the current financial situation of the crude palm oil mill supply chain as AGR is further deviated from the SGR. The stakeholders in the crude palm oil supply chain should thus monitor and control the financial implications due to the implementation of any improvement strategies, in order to ensure the sustainable growth of the business. Thus, the score of economic sustainability objective was the lowest compared to environmental and social sustainability objectives, due to the incorporation of this environmental strategy. The results reflect the fundamental principle of POSA framework, which was developed on the strong sustainability concept. Even-though the incorporation of the biogas trapping system brought more wealth to the business, economic sustainability measured how well this wealth was shared. The supply chain needs to improve its sustainability performance by spending its additional profit for the empowerment of the local community in order for the stakeholders in the supply chain to establish themselves as good corporate citizens. For example, increased number of smallholder equity and support schemes can be created for the local economy through.

The biogas trapping system implementation was not found to have immediate effects on the social sustainability PMs. The areas of social sustainability that were identified for potential sustainability improvement are information sharing with the local community, fair partnership and community involvement in the decision-making process.

The sustainability assessment of the improved supply chain using the POSA framework demonstrates that the incorporation of technological change or any modification in the supply chain could affect the TBL PMs positively and negatively with an ultimate aim of improving the overall sustainability score. The results presented in the comparative study are quantitative, traceable at every level of sustainability indicator. This would allow transparent and comprehensive evaluation of the sustainability performance results for decision making process and to formulate appropriate implementation strategies for achieving sustainable crude palm oil production.

CHAPTER 6. CONCLUSIONS

6.1 Introduction

The existing crude palm oil supply chain of Malaysia has sustainability challenges that need to be addressed. These sustainability challenges are plantation practices that are linked to deforestation, loss of species, GHG emission, soil and water pollution from its processes, as well as social conflicts due to inequality in land deals. There is a need for the development of well-defined sustainability indicators to enable stakeholders in the palm oil supply chain to address sustainability challenges. In this PhD research, a holistic sustainability assessment framework was developed, tested and verified for the most common crude palm oil production in Malaysia (Figure 6.1).

Figure 6.1: Timeline of the PhD Research as a Part-time Student

This chapter shows how 4 objectives of this PhD project were addressed through the publication of 5 refereed journals articles (Figure 1.2 in **Chapter 1**; Figure 6.1).

Paper 1 concluded that there were sustainability issues of palm oil production in Malaysia and the existing sustainability assessment methods for Malaysian palm oil production were not adequate to address these challenges.

Papers 2 and 3 presented how a holistic sustainability assessment framework known as Palm Oil Sustainability Assessment (POSA) was developed for achieving environmental, economic and social objectives of crude palm oil production supply chain in Malaysia.

Paper 4 demonstrated how the POSA framework was successfully applied to the most common Malaysian crude palm oil supply chain in the Borneo Island.

Paper 5 showed the flexibility of the framework in terms of responding to the changes associated with the incorporation of improvement strategies in the supply chain.

Four research objectives were addressed and the contribution to new knowledge is discussed as follows:

6.2 The Review of Malaysian Palm Oil Production and Its Sustainability Assessment

The literature review confirmed that the crude palm oil production needs to be assessed holistically against the strong sustainability principles, where the development is ecology-focused and society-driven, and both inter and intra-generational equity aspects of sustainability are taken into account (Brundtland (44) and Diesendorf (45)).

The subsequent review on the existing sustainability assessment methods adopted by the industries to measure sustainability performance of palm oil production, identified several weaknesses. For example, the existing methods are not comprehensive enough to measure triple bottom line objectives as some of them have indicators to measure only one objective, while some have indicators for all objectives, but they are neither quantifiable nor have threshold values to measure the sustainability gap. The review also suggested that these frameworks are not comprehensive and flexible enough to identify areas for suggesting improvement strategies.

6.3 The Development of a Holistic Sustainability Assessment Framework

The Palm Oil Sustainability Assessment Framework (POSA) was developed in 2 stages.

An integrated initial framework was proposed through a rigorous literature review to allow multi-criteria analysis for TBL assessment while complying with strong sustainability principles and to enable the quantification of the initial set of TBL indicators (HPIs, KPIs and PMs). Mathematical models were developed to calculate the scores of TBL objectives of crude palm oil production. The framework was tested using hypothetical data and had identified potential areas for further improvement. The determination of relevance and importance of PMs was identified as the next essential task to further improve the framework.

The framework was further revised by receiving collective feedback from 4 categories of stakeholders, including the government, the industries, the academicians, and the local people/ NGO. The indicators (HPIs, KPIs and PMs) were finally selected based on the feedback. One new PM (species loss) was included and the criteria for ranking value of 2 PMs (plantation practice and local community involvement in decision making) have been modified following the suggestions of the respondents. The weight for each PM was calculated using their level of importance obtained from the survey. Threshold values of PMs were also selected through the literature review and consultation process in order to determine the gap to achieve the sustainability target. The POSA framework was finally tested using hypothetical data to ascertain its scientific validity.

6.4 The Sustainability Assessment of Crude Palm Supply Chain in Malaysia

A sustainability assessment was carried out for the most common Malaysian crude palm oil supply chain located in Borneo Island, where FFB sourced from both large and small plantations, trees were planted on mineral soil, and the palm oil mill used an open-pond system for POME treatment (i.e. without a biogas trapping system). The sustainability score of this supply chain using the POSA framework was determined as 3.47/5, meaning that it performed below the sustainability threshold (<5). The TBL sustainability hotspots identified were GHG emission, lack of biomass waste recycling and recovery, smallholder inequity, improper plantation practices, lower average wages and local employment problems.

The application of POSA framework to assess the sustainability performance of the most common Malaysian crude palm oil supply chain had identified strategies for further improvement of the sustainability performance. Some of the improvement strategies proposed were the incorporation of a biogas trapping system to capture the methane gas from POME, the use of biofertilizer to reduce carbon intensive synthetic fertiliser, sourcing of FFB from plantations at closer proximity to reduce fossil fuel consumption during transportation, and the introduction of patch planting/successive strips of oil palm trees and variable rotation at plantations to increase landscape heterogeneity.

6.5 The Verification of Sustainability Assessment Framework through Comparative Study

A whole system of KUBOTA biogas cum polishing plant was considered in the existing crude palm oil supply chain as a replacement for an open-ponding system to trap biogas and to avoid the soil and waste contamination associated with POME. This improved crude palm oil supply chain was reassessed to determine sustainability implications associated with this technological change. The results of this supply chain were then compared with the baseline supply chain (i.e. **Chapter 4**; **Appendix 4 – Paper 4**)

The incorporation of the biogas trapping system into the baseline crude palm oil supply chain made significant improvement to some environmental performance measures (i.e. GHG emission and biomass waste recovery rate). The additional investment and incremental operation and maintenance cost however, had caused a further negative deviation of Actual Growth Rate from the Sustainable Growth Rate. Another economic hotspot associated with this change in the supply chain was the sharing of economic power with the local community.

The follow up sustainability assessment thus triggered further improvement strategies, such as introduction of financial strategies by the stakeholders in the supply chain (e.g. reducing debts to make productive use of cash in hand) to ensure business continuity during any sort of modification in the supply chain, and to offer larger smallholder equity, create more local employment by reducing dependence on foreign workers and by offering higher wages. Despite the aforementioned positive and negative impacts of the incorporation of the improvement strategy, the overall sustainability score of the supply chain was increased from 3.47/5 to 3.59/5.

The comparative study concluded that the POSA framework is flexible enough to handle any changes in the supply chain. This also allows an iterative process by involving a variety of improvement strategies until a complete sustainability is achieved (5/5). In this way the POSA framework will assist stakeholders in the supply chain to select and implement sustainable development strategies and influence decision makers in the policy making process.

6.6 Contribution to New Knowledge

By achieving the 4 objectives, the research filled the following knowledge gaps: -

- A definition of sustainable palm oil production based on strong sustainability principles was developed in order to develop an appropriate framework for sustainable palm oil assessment.
- This research identified the shortcomings of existing tools and methods in measuring and achieving sustainable palm oil production.
- This research developed a new sustainability assessment framework to address shortcomings in existing tools and methods to evaluate sustainability of crude palm oil production. The framework offers a holistic assessment structure which allows multi-criteria analysis and a complex sustainability assessment for palm oil production in a systematic manner. This assessment framework could be applied in other industries of similar nature, nationally and internationally, by using region and industry specific indicators.
- The outcome of sustainability assessment of the most common crude palm oil production in Malaysia, had identified TBL hotspots in the supply chain in order to determine sustainability improvement strategies.

6.7 Recommendation/ Future Research

Some recommendations for future potential research have been made as follows: -

- The sustainability assessment showed that the supply chain is still performing below the sustainability threshold. Several hotspots were pointed out and these need to be resolved to close the gap between actual performance and the TBL sustainability targets/threshold values.
- The palm oil industry involves a wide range of stakeholders, including government regulators, industry players, consumers, and local people. The industry is therefore dynamic based on the needs of these stakeholders. Any change could occur in the legislative requirements, government directives, and even international treaties as needed. Besides, technologies are developed continuously to improve the productivity and sustainability performance of the

supply chain. Therefore, sustainability threshold values need to be adjusted accordingly by taking into account these changes in politics and international trade requirement, as well as by utilizing new findings of research and technology development. It is therefore important to review the ranking criteria, threshold values of all performance measures periodically to ensure that the relevance of PMs of the POSA framework are up to date.

- The current project is limited to basic supply chain of crude palm oil production. The system boundary of the assessment framework could be extended by incorporating other downstream processes, including the refinery and manufacturing processes to produce finished products e.g. cooking oil, biodiesel, margarine, shortening.
- Besides, the accuracy in estimating some performance measures could be improved, such as species loss could be measured using scientific methods (e.g., the species–area curve rather than collective feedback), while soil nitrate levels could be measured directly with a flow injection analyser rather than knowing the value of pH in water way(32). Finally, instead of total energy input, net energy input can be considered in the calculation of the energy input output ratio.

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APPENDICES:

Appendix 1 – Paper 1

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Statement of Contribution

To Whom It May Concern,

I, Chye Ing LIM, contributed to literature review, methodology formulation, results discussion, analysis and writing (80%) of the paper/publication entitled:

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The remaining 20% of this paper/ publication was contributed by Wahidul K. Biswas (10%) and Yudi Samyudia (10%).

Signature: Date: 31 March 2019

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Co-author 1: A/Prof Wahidul K. Biswas Date: 31 March 2019

Co-author 2: Prof. Yudi Samyudia Date: 31 March 2019

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Review of Existing Sustainability Assessment Methods for Malaysian Palm Oil Production

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Abstract

Malaysia is the second largest palm oil producer in the world. Palm oil production contributes to 6.4% of its gross national income and is important to the socio-economic growth of the country. Palm oil is cheap, high-yield and versatile in various applications. However, the Malaysian palm oil industries are facing enormous challenges due to environmental criticism from pressure groups, green consumerism and increasingly stringent sustainability criterion of importing countries. As a result, various assessment methods have been applied to assess the sustainability performance of palm oil production in Malaysia. This paper reviews how the stakeholders define sustainable palm oil, the effectiveness of existing sustainability assessment through tools (e.g. LCA), standards (e.g. ISPO, ISCC) and legislative requirements (RFS2, REDcert) to identify gaps and barriers to achieve environmental, economic and social objectives of sustainable palm oil production. The gaps and barriers identified would be the basis for developing a holistic framework to attain sustainable palm oil production in Malaysia.

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Keywords: Palm oil production; sustainability; sustainability assessment; Malaysia

1. Introduction

The worldwide demand for palm oil has been growing over the past few decades at a rate of 7.1% per annum[1]. The versatility of palm oil in various applications has made it one of the top seventeen oils and fats sources in the world [2]. It does not only assist in meeting the demand of edible oil worldwide, but is also used extensively for oleo-chemicals and biofuel production. Most importantly, palm oil is expected to be a promising alternative fuel to slow down the depletion rate of non-renewable fossil fuels. Because of her position as the second largest palm oil producer in the world, Malaysia should thus, endeavor to maintain its continuous palm oil production in a sustainable manner.

Palm oil has been proven as a useful product which had accelerated its commercial operation. This oil is enriched with antioxidants and has beneficial effect on cholesterol level [3]. Its production cost is at least USD 200 per tonne cheaper than rapeseed oil, and is also cheaper than groundnut, sunflower and soybean[4]. This oil supplies 31.3% of global oil and fat demand in 2011, meeting the needs of 3 billion people in 150 countries [2]. In addition, it contributes to 57% of world vegetable oil exports, which is three times more tradable compared to soybean. The global market has thus become increasingly dependent on palm oil, which is expected to hit a demand of 62-63 million tonnes by 2015 [4].

Malaysia currently accounts for 38.7% of the world's palm oil production. Palm oil industries generated export earnings of MYR73.26 billion or USD22.32 billion in 2012[5]. The oil palm industries are expected to continue to play a pivotal role to achieve both GNI (MYR178 billion or USD57 billion) and job creation (1.3 million) targets of the Malaysian Government by 2020[6]. These facts show that palm oil industries are not only inevitable to Malaysia for its socio-economic development but could also contribute to achieve a sustainable solution for the world's food and energy demand.

Whilst palm oil could offer sustainability benefits by improving Malaysia's socio-economic conditions, these industries have been criticized particularly by international pressure groups, including Greenpeace, Rainforest Action

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Network and World Wildlife Fund (WWF) for current unsustainable production practices [7]. There is also a green consumers' demand for sustainability assurance.

The intensive farming practices and unplanned land use have led to deforestation, loss of species and social conflict between local community and plantation companies. The application of synthetic chemicals (e.g. pesticide and herbicide) has caused land contamination, soil and water pollutions [8], while the increased dependence on fossil fuel for processing and farming operations resulted atmospheric emissions and fuel scarcity, and the emissions of methane from the anaerobic digestion of organic waste such as palm oil mill effluent resulting global warming impact (POME) [9]. Thus, it raises a question as to how to establish sustainable palm oil industries in Malaysia. In order to address this research question, exiting works both directly and indirectly related to the sustainability assessment of Malaysian palm oil industries need to be reviewed as a basis for developing a holistic approach for sustainability assessment to regain the stakeholders' confidence in the supply chain.

A wide range of research has been conducted by researchers to address the socio-environmental problems in the palm oil industry. This paper reviews these issues, the tools and standards used for sustainability assessment, in order to identify gaps and barriers to achieve environmental, economic and social objectives of sustainable palm oil production.

2. Method of review

This study forms part of a rigorous literature review of supply chain management of the palm oil industry. All level of stakeholders along the palm oil supply chain related to Malaysians' context were identified. Their opinions and findings about palm oil sustainability were reviewed through newspaper and magazine articles, organizations' websites, published surveys, national statistics documents, official reports and papers. Palm oil sustainability assessment methods and tools were reviewed through refereed papers, recent palm oil related directives, legislations and standards. The definitions, methods and tools for assessing sustainable development and sustainability were reviewed, analysed and compared against the findings on existing palm oil industries' sustainability performance.

Papers included were identified from a structured keyword search in the following databases: Elsevier Science Direct, Springerlink, Wiley Interscience, and Emerald Insight. Keywords included "palm oil", "social impacts", "environmental management", "supply chain", "sustainable/sustainability", "environment", "life cycle assessment" and "sustainability assessment". Sources were then selected according to the following criteria:

- Scientific research and official publications from the last 10 years;
- Refereed research articles
- Nationally recognized media publications
- Published in English

Results were then categorised into sustainability issues of Malaysian palm oil production from the triple bottom line aspects, state of the art sustainability assessment methods of palm oil production, and the weaknesses, barriers in these assessment methods to achieve the sustainability objectives.

3. Review of Malaysian palm oil production

Palm oil has its positive implications to sustainable development but its rapid growth in Malaysia has also led to adverse social, economy and environment impacts.

3.1. Environmental implications

Oil palm could help achieving high land use efficiency as its yield is about 10 times more than other leading oilseed crops[2]. The energy yield ratio of palm biodiesel is 3.53, which is more than double of rapeseed biodiesel [10], and also performs better than other competing oils, including soybean[4], coconut and jatropha[11]. In terms of greenhouse gas (GHG) emissions, a carbon saving benefit of 38% is achievable associated with the replacement of conventional diesel fuel with palm biodiesel [10]. Oil palm plantation also allows agro-forestry and livestock crop integration [12], thus could increase the intensification of land use in Malaysia.

The plantation area of oil palm in Malaysia has increased by 150% over the past 30 years [8]. The fragmentation of forest associated with this man-made monocultures has adversely affected the forest ecological functions and threatens the already endangered species e.g. orangutans, elephants, tigers and rhinos[13]. Land clearing activities for oil palm plantation have been identified as the root cause for forest and peatland fires[7] in Southeast Asia each year, which affect the health of millions people in the region, suffered from pneumonia and other respiratory diseases [14].

Palm oil production has also resulted in increased carbon footprints (life cycle GHG emissions). Drainage and burning of peatland forest for palm oil production alone released about 2 billion tonnes of CO_2 equivalent GHG emissions each year, contributing to 4% of global annual emissions [7]. Besides, anaerobic digestion of organic waste such as palm oil mill effluent (POME) causes methane emissions, which has strong global warming impact [9]. Intensive farming practices associated with the increased commercial operation such as the application of N-fertilizer for palm oil plantation could lead to N_2O emission which is 298 times more powerful than CO_2, potentially contribute to even more global warming than the intended cooling through replacing fossil fuel in biofuel application [15]. As a result, the carbon footprint of palm oil (2.8-19.7 kgCO_2 equivalent per kg of palm oil) is 2 to even 18 times [9] higher than other plant based oil (e.g. 1.2 kgCO_2 equivalent per kg of soybean) [16]. Apart from GHG emissions, the use of pesticide and herbicide is causing land contamination, soil and water pollutions [8].

In general, palm oil is neither carbon neutral nor free from other associated environmental impacts such as climate change, use of fossil fuels, respiratory inorganic, acidification/ eutrophication, eco-toxicity etc.

3.2. Social impacts

From the social perspective, palm oil industries offer income source to the rural population, and has created approximately half a million employment opportunities and reduced urban migration [5]. About 14% (5.3 million hectares) of the total oil palm planted area in Malaysia were planted by independent smallholders [17]. The involvement of local farmers could potentially play a significant role in poverty alleviation, and improve healthcare and education[18].

On the other hand, the palm oil industries have been found to disregard the rights and interest of the local community - the indigenous people in particular. The indigenous people loss their native customary land to large plantation companies due to bribery given to their village head [19] and promises of welfare and income[13] which were later found breached. On top of that, the community had to carry the debt burden due to unequal profit sharing in the contract. Some plantation sites were also reported of using children as low-paid labours [20].

The conversion of forest to palm oil plantation sites has also affected the livelihood of many indigenous people as 83.3% of them have reduced access to the forest resources and there was a significant reduction in fish stocks due to water pollution[18]. Their traditional customs and cultures are disappearing, and many cultural sites e.g. the sacred ancestral burial ground, were destroyed and replaced by oil palm plantations[19]. These experiences present social inequity, which are predominantly from upstream activities of palm oil production. If palm oil is to be considered as a solution to the world's food and energy needs, intra-generational social issues are equally important for achieving sustainable palm oil production.

3.3. Economic impacts

Palm oil industries stand as the fourth largest contributor (6.4% of gross national income) to the Malaysian's economy[6] and is foreseeable to grow continuously due to its versatility, relatively high yield and low price. An economic concern is that farmers are switching from non- economic crops such as cocoa, rubber and coconut to oil palm [4] which could lead to monoculture economy in Malaysia.

Palm oil companies are also facing business risks and experiencing hurdles to run their commercial operation due to unsustainable production. For example, Greenpeace had forced Nestlé not to buy palm oil from Sinar Mas, an oil palm plantation company and made HSBC dropped their investment from it due to its bad reputation of unfriendly environmental practices[21].

Combined efforts of pressure groups have created critical mass and influenced government agencies to enable industries to source green palm oil through government directives. Rainforest Action Network (RAN) for example, worked with Environmental Protection Agency, U.S. to ensure it excludes palm oil-based biofuels from the federal renewable fuels mandate[22]. The United Kingdom on the other hand, is working towards achieving 100% sourcing of credibly certified sustainable palm oil by the end of 2015 [23]. To qualify for the EU Renewable Energy Directive (RED) Biofuels Sustainability Scheme, where incentive is received from EU member states, EU RED requires biofuel to emit at least 35% less greenhouse gas emission than the fossil fuels since 2008 [24]. Palm oil produced in Malaysia in a business as usual scenario offered only 19% GHG saving which is far less than European and US threshold values[25]. As a result, Malaysia had pledged to keep at least 50% of its land as forest cover in Earth Summit in 1992 and Rio+20 in 2012[26].

Thus it is a challenge for the existing Malaysian palm oil producers to meet these stringent targets to enhance their international trade and commercial viability. The supply chain needs to produce socio-environmentally friendly and yet more productive palm oil to meet the requirements of international treaties, new developments in international trades and green consumerism to be economically sustainable in the future.

3.4. Sustainability of Malaysian palm oil industries

The current scenario of Malaysian palm oil industries neither conforms to the definition of Brundtland [27] nor Diesendorf [28]. According to Brundtland (1987), "sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Palm oil industries cause the lack of cultivable land for diverse crops, the loss of biodiversity and environmental footprints during the production processes which could affect the future generation in Malaysia.

Diesendorf (2000) modified Brundtland's definition by incorporating intra-generational equity which is the equity between same generations and also emphasised that ecological and social aspects shall be primary objectives and they cannot be traded off with economy development. The existing Malaysian palm oil industries have been criticized for not addressing intra-generational social equity as the livelihood of local community was affected due to palm oil plantations.

Also the existing palm oil production appears to follow weak sustainability represented by an interlocking diagram (Fig. 1). Firstly, the existing palm oil production is economic-focused rather than ecological focused and trade-offs are made between economic development (i.e. Gross Domestic Product) and environmental quality. The oil palm production can increase GHG sequestration, allow livestock and crop integration and increase income and generate employment, but it is currently causing the disappearance of animal species and cultural values in the forest area. Secondly, these industries started with economic imperatives, rather than considering ecological imperatives before converting forest to oil palm plantation to avoid damaging critical natural capital. Thirdly, intergenerational equity allows substitution of human-made capital for natural capital but does not involve substantial conservation of biodiversity, ecological integrity, cultural diversity and other capital, and the empowerment of the local indigenous community.

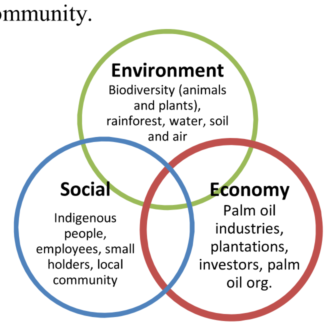

Fig.1: Current Scenario of Malaysian Palm Oil Industries with Limited Commitment of palm oil stakeholders in sustainability

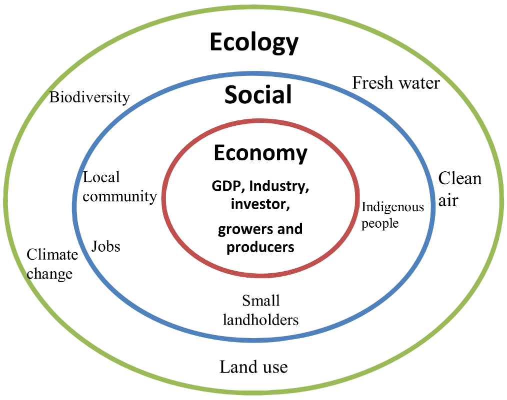

Fig. 2: Sustainable Palm Oil Production

Therefore, a definition has been developed specifically for the Malaysian palm oil industries, which is represented by nested egg diagram (Fig. 2) meaning that ecological limits or constraints are sat on economic activity to avoid damaging critical human and natural capital.

"Sustainable palm oil production is defined as the production that does not cause the loss of bio-diversity, does not increase GHG emissions and associated ecological footprints, does not affect the livelihood of the indigenous people; while enhancing commercial operation, sharing economic growth with the local community through employment and fair trade."

This definition has been used as a benchmark to assess the existing work on sustainability assessment of palm oil production in Malaysia and the framework that will be based on this definition would be able to interpret the interrelationship and interaction between three pillars of sustainability.

4. Review of sustainability assessment of Malaysian palm oil industries

4.1. Definition of sustainable palm oil production by different organizations

The sustainable palm oil definitions provided by green consumers, Malaysian Sustainability Palm Oil (MSPO), Round Table on Sustainable Palm Oil (RSPO) and International Sustainability & Carbon Certification (ISCC) have neither explicitly mentioned inter-generational and intra-generational equity issue, nor taken ecologically driven sustainability approach. None of these aforementioned definitions took into account three pillars of sustainability, and are, therefore, considered as weak sustainability.

4.2. Life cycle assessment

MPOB conducted a full life cycle assessment of the Malaysian oil palm supply chain following the ISO 14040-44 standards in 2006-2010 to provide baseline information on the environmental performance of the industry [29]. Most of the impacts identified are resulting from upstream processes due to lack of environmental management strategies[30]. A major weakness of the life cycle assessments conducted by MPOB is that it only assessed the environmental aspect and it did not include the effect of indirect land use change (ILUC) which potentially has great contribution to the GHG emission. Besides, contribution in impact areas are presented in eco-point unit, quantitative value of GHG emission per functional unit was not published.

4.3. Palm Oil Sustainability Standards/ Certification Schemes

Malaysian palm oil industries began to work with RSPO in year 2004 to promote the growth and use of sustainable palm oil through co-operation within the supply chain and open dialogue between its stakeholders [31]. RSPO is an internationally recognised, membership-based organisation for oil palm growers, processors, trader and consumer goods manufacturers who use palm oil in their products. Through stakeholders' dialogue and voluntary involvement, RSPO introduced RSPO Certification Scheme based on 8 principles, each of which has a list of elaborated criterions [32]. Certified manufacturers may label the RSPO trademark on the products.

Apart from RSPO, there is another certification scheme which was developed by the ISCC. Sustainability requirements of ISCC towards production of biomass include six broad principles [33]. These certification schemes contain broad, general principles that require only a management system to be in place rather than demand for specific sustainability performance. For example, RSPO requires that GHG emissions to be minimised [34] without setting a specific target for achieving international standards.

Until March 2014, only 16% of global palm oil produced are RSPO certified, of which 43.95% are from Malaysia[31] and as of May 2014, 426 ISCC certificates have been issued to oil palm plantation and oil mills which comply with the principles and criterion of the certification scheme[35], covering only a small group of players in the market.

4.4. Trade requirements and Directives of importing countries

The United States' Renewable Fuel Standard 2 (RFS2) requires palm oil to emit 20% - 60% less lifecycle GHG emissions than the conventional diesel to be eligible for a Renewable Identification Number. According to EU RED, sustainable biofuel can neither use land with high carbon stock (wetlands, continuously forested areas, peatlands) nor source raw material from land that has high biodiversity value (primary forest, bio-diverse grassland, nature protected areas) . In addition, a minimum of 35% of GHG saving need to be achieved by replacing fossil fuel. The number is to be increased to 50% in 2017 for current plantation and 60% in 2018 for new plantation[24].

5. Weaknesses of existing sustainability assessment

Despite various efforts made to achieve sustainable palm oil scenarios by both industries and researchers, there are still opportunities to improve the sustainability assessment process by overcoming the existing weaknesses which are as follows:

5.1. Green Design Versus Greenwashing

Whilst RSPO was initiated by the industries to legitimate palm oil to promote its use and development, the objective was actually economic driven rather than sustainability-focused[36]. RSPO members and executive board are dominated by the industry representatives who perceive sustainability certification as means to ensure business continuity. Palm oil producers holding RSPO memberships, are only stakeholders giving their opinions to the organization but are not necessarily the certified palm oil producers [37]. This often misleads the consumers. Furthermore, the GreenPalm certificates that is endorsed by RSPO, allow companies to purchase the certificates from the RSPO certified growers in the GreenPalm Market. There is an absence of accountability which in some instances could not prevent the companies to procure palm oil from the uncertified growers not complying with the environmental regulations [7, 38]. A palm oil sustainability assessment framework that focuses on achieving sustainability objectives [see section 6], and also strengthens accountability of palm oil industries needs to be developed to truly assess and improve the Malaysian palm oil supply chain.

5.2. Market Share of RSPO Certified Palm Oil growers

The certification schemes like RSPO and ISCC have some inherent weaknesses as these schemes only certify palm oil production from specific plantation areas but not on the basis of overall performance of the plantation company[39]. Hence, plantation companies could have some of their plantations certified to meet the requirements of the EU and US market. The remaining uncertified plantation sites offers cheaper price of palm oil (as certified palm oil will cost 8-15% more than the uncertified ones) to access the Chinese and Indian markets, where sustainability is not criteria for imported items[36]. Hence, a sustainability assessment framework could not only enhance the corporate images of these industries but also could protect the industries' profits and promote green market.

5.3. Choice of sustainability indicators

Even with RSPO certification, the palm oil production is not truly "sustainable" [40]. RSPO's criterion 7.3 requires that 'new plantings since November 2005, have not replaced primary forest', which means deforestation for plantation prior to the commencement date will not be taken into account, and yet certified plantation can trade the palm oil produced from the old plantings as RSPO certified palm oil[39]. Greenpeace[41] investigated that these standards are 'far too weak' as these standards cannot prevent the destruction of forests and peatlands to meet the growing demand for palm oil. The RSPO principles and criteria do not include the banning on peatlands and high carbon stock forests, and without that RSPO standards are not enough for businesses to meet zero deforestation and low-carbon supply targets [42]. A holistic sustainability assessment framework will thus incorporate ecosystem and heritage conservation as criteria for sustainable palm oil production.

5.4. Comprehensiveness of existing sustainability assessment

Current sustainability assessments applied on the palm oil industries are not comprehensive enough to reflect a holistic picture. Life Cycles Assessments along the supply chain have only reflected the environment performance of the industries. Social, economic performances are not evaluated using this method. Besides, there are common weaknesses of the existing LCA on palm oil production. There exists a large uncertainty due to assumptions made (e.g. fixed FFB yield), absence of actual site data for LCA inventories calculation, and the use of generic data which cannot provide representative results for decision making purposes.

5.5. Holistic approach of existing sustainability assessment

Among all, RSPO and ISCC offer relatively a more holistic assessment covering environment, economy and social aspects of sustainability. However, RSPO certification scheme has a lack of environmental and social safeguard as it does not include the Greenhouse Gas (GHG) emissions standards[39]. In addition, there is no adequate specific and quantifiable action for planning, implementation and monitoring to reduce pollution and emissions and also there is an absence of transparently when consulting with growers, mills, smallholders and other local business.

6. The proposed sustainability assessment framework

A more holistic sustainability assessment framework could be structured using the approach followed by IISD (2002) and van Berkel et al. (2008) [43, 44].

According to these approaches, each triple bottom line objective consists of a number of headline performance indicators (HPIs). These indicators are the highest aggregation level for the performance measurement against sustainability objectives. Each HPI is then aggregated into key performance indicators (KPIs) which further describe key impact areas of each HPI with respect to palm oil production that could foster or impede the achievement of each sustainability objectives. The performance measures (PMs), which is the lowest level of aggregation will be established to give quantitative measures for indicators that could contribute to each KPI[43]. The review conducted in section 3, 4 & 5 will provide the basis to discern appropriate HPIs, KPIs and PMs. For example, environmental integrity and benefits could be one of the HPIs for environmental sustainability objectives of palm oil production [45], where the KPIs contributing to this HPI could be biodiversity, air quality, ecological capacity. There are number of PMs for each KPI, for example, the PMs could be number of species and species richness for biodiversity.

7. Conclusions

The review of existing sustainability assessment tools for Malaysian palm oil production pinpoints some shortcomings in their existing framework to assess sustainability of palm oil industries. There is a need of a holistic approach for measuring the right indicators using a comprehensive sustainability framework for the palm oil supply chain, specifically addressing upstream processes of crude palm oil production where most impacts occur. The framework proposed would be able to assess the true sustainability performance for decision making and to provide guideline for improving sustainability performance. The policy makers will be benefited from making strategic decisions and policy formulation which will ultimately restructure the sustainability supply chain of the Malaysian palm oil industries.

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Appendix 2 – Paper 2

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Statement of Contribution

To Whom It May Concern,

I, Chye Ing LIM, contributed to literature review, methodology development, hypothetical data collection, results analysis, discussion and writing (80%) of the paper/publication entitled:

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The remaining 20% of this paper/ publication was contributed by Wahidul K. Biswas.

Signature: Date: 31 March 2019

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Co-author 1: A/Prof Wahidul K. Biswas Date: 31 March 2019

sustainability

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Article

An Evaluation of Holistic Sustainability Assessment Framework for Palm Oil Production in Malaysia

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Abstract: Palm oil based biodiesel offers an alternative energy source that can reduce current dependence on conventional fossil fuels and may reduce greenhouse gas (GHG) emissions depending on the type of feedstock and processes used. In the Malaysian context, the palm oil industry not only provides high-yield, renewable feedstock to the world, it brings socio-economic development to the Malaysian rural community and contributes to the national income. However, the sustainability of palm oil remains controversial, due to deforestation, pollution and social conflicts associated with its production. Sustainability assessment is vital for the palm oil industry to identify weaknesses, improve its sustainability performance and improve consumer confidence. This paper proposes a holistic sustainability assessment framework for palm oil production with the aim to address the weaknesses of existing palm oil sustainability assessment methods. It identifies environmental, social and economic Headline Performance Indicators, Key Performance Indicators and their Performance Measures in crude palm oil production in a structured framework. Each quantitative/semi-quantitative performance measure is translated into Likert Scale of 1–5, where 3 is the threshold value, 5 is the ideal condition, and 1 is the worst case scenario. Calculation methods were established for the framework to provide quantitative assessment results. The framework was tested using a hypothetical example with data from existing studies. The results suggest that crude palm oil production in Malaysia is below the sustainability threshold. Evaluations of this sustainability assessment framework also demonstrate that it is a comprehensive assessment method for assessing sustainability of feedstock for biofuel production.

Keywords: sustainability assessment; assessment framework; palm oil production

1. Introduction

Malaysia is known as the major palm oil producer in the world. The palm oil industry stands as the fourth largest contributor to the nation's economy and contributes to 6.4% of gross national income [1,2]. The palm oil industry creates job opportunities, alleviates poverty and improves healthcare as well as education in rural areas [3]. Oil palm has been recognized as a high-yield oil tree compared to other feedstocks. The versatility of palm oil in oleo-chemical applications, food and biofuel production has also led to rapid growth of this industry.

Whilst palm oil could offer sustainability benefits by improving Malaysia's socio-economic and environmental conditions, these industries have been criticized particularly by international pressure groups, including Greenpeace, Rainforest Action Network and World Wildlife Fund (WWF) for current unsustainable production practices that has led to deforestation, increased greenhouse gas (GHG) emissions, and the loss of biodiversity [4]. There is also a pressure from environmentally conscious consumers for palm oil industries to achieve sustainability criteria [4–6]. Hence, there is a need for a holistic sustainability assessment method for palm oil production in order to identify the area of strengths and weaknesses, which will enable decision makers to improve the supply chain sustainability practices, and hence offer more confidence to the consumers.

Sustainable palm oil production is defined as the production that protects the natural environment, promotes intra and inter-generational equity, while enhancing commercial operations, and sharing economic growth with the local community through employment and fair trade, following Lim *et al.* [7–9].

A thorough review of literature published to date suggests that this aforementioned definition could substantially strengthen the framework for assessing sustainability of Malaysian palm oil industries [10–20]. Existing sustainability assessment that involves a number of assessment methods including Life Cycle Assessment, measurement of palm oil sustainability standards and certification schemes have not adequately addressed the sustainability of Malaysian palm oil production due to the following reasons [16,21,22]: the absence of Triple Bottom Line (TBL) assessment, use of ambiguous or unmeasurable indicators (e.g., Criterion 6.11 of Roundtable on Sustainable Palm Oil (RSPO) principles would require growers and millers to contribute to local sustainable development as "wherever appropriate", while the indicator is "demonstrable contribution to local development that are based on the results of consultation with local community". However, there is no clear measure on how they should contribute, and to what level these contributions should be considered as "appropriate" and "demonstrable"), lack of relevant sustainability indicators (e.g., RSPO excludes banning of plantation on peatlands and high carbon stock forests, as well as the impact of deforestation that took place before November 2005), greenwashing, and incompliance with import regulations [4,7,23] are some of the weaknesses in existing sustainability assessment methods for palm oil production.

Apart from the aforementioned weaknesses of the existing sustainability assessment methods, there are some other factors that have impeded the successful application of sustainability assessment frameworks (e.g., the perceived complexity associated with sustainability assessment by the industrial stakeholders including plantation companies and millers) [24], the hurdle to obtain a large number of information for determining useful indicators [25], lack of knowledge in sustainability aspects, *i.e.*, economics, environmental and social science and analytical ability to interpret the indicators and results [26–28], and finally the involvement of time and cost in the detailed assessment process. Therefore, a user-friendly framework is necessary not only to overcome the aforementioned weaknesses and gaps of sustainability assessment in the context of palm oil production, but also to encourage wider application of self-examination on sustainability performance among the stakeholders, thus closing the "research–implementation gap" [29].

This paper presents the development and implementation of a holistic sustainability assessment framework for palm oil production in Malaysia. Firstly, various models of a sustainability assessment framework have been evaluated. Secondly, the development of a sustainability assessment framework consisting of social, economic and environmental indicators relevant to the contexts of palm oil production in Malaysia has been discussed. Thirdly, information about crude palm oil production based on national statistics and other existing research has been used to test the applicability of the framework. Fourthly, the formulae for calculating the assessment results have been presented as part of testing the framework. Finally, the sustainability assessment framework has been analysed using TBL indicators.

2. Theoretical Framework of Palm Oil Sustainability Assessment

2.1. Sustainability Assessment and Its Purpose

Sustainability assessment is commonly defined as a tool to identify, predict and evaluate potential environment, social and economic impacts of an initiative to assess sustainability [30]. The assessment will identify barriers to achieve sustainability and, accordingly, it will propose the best available options for planning and decision making [31].

2.2. Various Frameworks of Sustainability Assessment

Various sustainability assessment frameworks have been proposed from different contexts. Since sustainability assessment is aimed to examine the implication of an initiative to attain "sustainability", the concepts as well as approaches of these frameworks vary with the definitions of sustainability.

2.2.1. Weak *vs.* Strong Sustainability

The existing sustainability approach is grounded on two major schools of thoughts where one promotes a "weak sustainability" approach or social, economic and environmental bottom lines are treated with equal importance [9]. On the other hand, the Federal Office for Spatial Planning of Switzerland believes that sustainability assessment should identify imbalances and deficiencies between environmental, social and economic dimensions, in order to optimise the benefits and attain long-term equilibrium between these three dimensions. Trade-offs are permitted between three dimensions, provided that the basic social, economic and environmental requirements are met [30]. A similar approach is used in the studies of Devuyst for transportation management plans [31] and Kucukvar for the construction industry [32].

Pope *et al*. however, warned of taking such a sustainability assessment approach without critical debate as it might overly promote the prevailing economic agenda and undermine the environmental factors [33]. This echoes a strong sustainability approach which is the second school of thought, as defined as "Sustainable development comprises various types of economic and social development that protect and enhance the natural environment and social equity" [9]. In this concept, natural resources are finite, and therefore sustainability means finding a way to live within the carrying capacity of natural systems and this considers both inter- and intra-generational equity where the latter is aimed at achieving social equality. A similar principle was applied by Ekins *et al*. where maintenance of critical natural capital is regarded as a priority [34], rather than man-made capital and the built environment.

The sustainability assessment framework varies with the concept adopted. It affects the approach, determination of assessment structure, evaluation of methods and, hence, the outcome of the assessment process. Thus, the conceptual framework of the current research is based on the strong sustainability concept that is ecosystem focused, as it takes into account biophysical limits, social equity and eco-sufficiency.

2.2.2. Three Categories of Sustainability Assessments

Ness *et al*. categorize sustainability assessment into three approaches, *i.e.*, indicators/indices, product-related assessment and integrated assessment [35]. Indicator approaches use sets of qualitative dimensions which could be aggregated into quantifiable measures that assess sustainability in the form of index [35]. It is simple, easy to understand, and flexible in allowing integration of different sustainability elements.

Product-related assessments are usually more focused on one facet of sustainability, e.g., life cycle assessment that focuses on overall environmental impact of a specific product, life cycle cost analysis that evaluates the financial impact and product material/energy analysis that measures only the material/energy consumption. It provides quantitative results based on specific and thorough evaluation, but on the other hand, it usually involves a large data set and is limited to certain sustainability elements.

To incorporate a deeper and broader scope of sustainability elements [36], integrated assessments are introduced as the third type of approach. Integrated assessment combines two or all three sustainability elements. It includes the qualitative assessment, e.g., conceptual modelling that presents the relationships between different elements in the form of flow diagrams, flow charts, or causal loop diagrams [35,37], and Multi-Criteria Analysis (MCA) that allows evaluation of competing criteria such as the assessment approach used in RSPO certification. Integrated assessment could also be quantitative, e.g., hybrid of LCA with Environmental Impact Assessment (EIA), Input Output Life Cycle Assessment (IOA) and other methods [38] and remodeling of other elements, *i.e.*, economic and social aspects, into LCA [39].

2.2.3. The Circular, Triangular and Network Structure

As sustainability assessment involves complex concepts and utilizes data, the assessments are usually presented in a matrix or diagram with different structures. The sustainability indicators and their relationship with different elements of sustainability could be presented in three types of structures, *i.e.*, circular, triangular and network.

For a circular structure, a circle is divided into segments that represent each dimension, and each segment is further divided into smaller segments where each smaller segment represents a sustainability indicator. Performance of each indicator could be rated based on a quantitative or qualitative Likert scale. The results could therefore be presented in a spider-web diagram that is easy to interpret. For example, a circular structure is used in sustainability assessments for urban planning [40] and social sustainability assessments [41] (Figure 1).

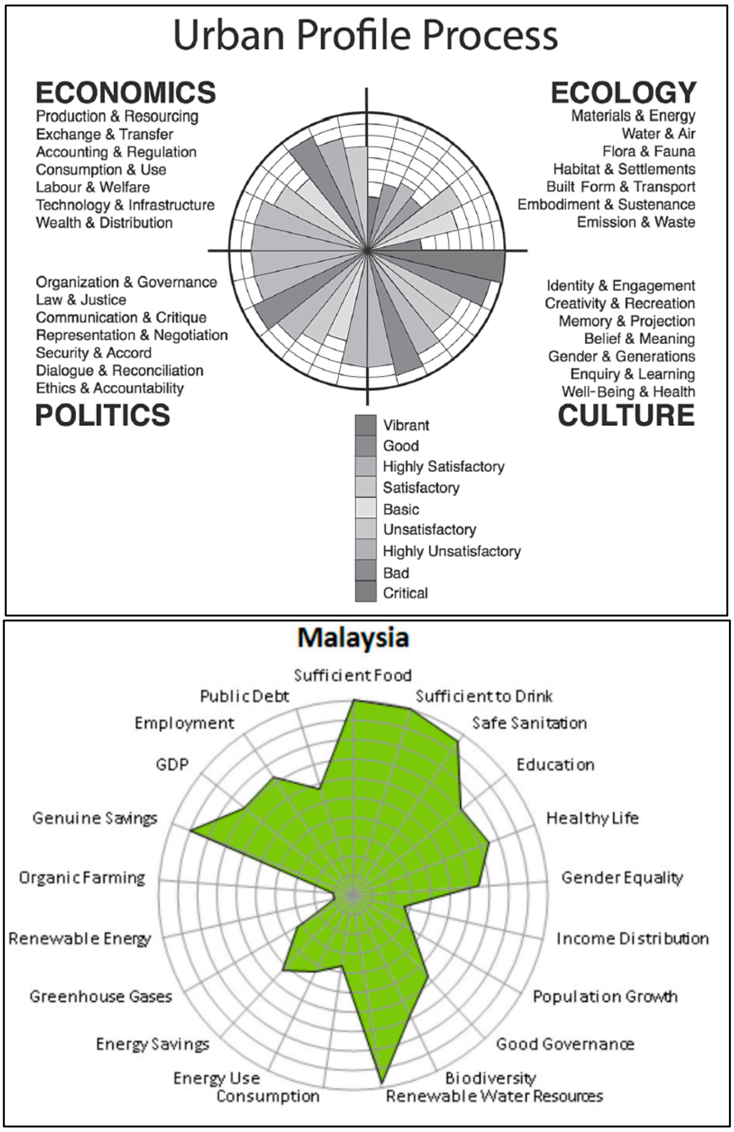

Figure 1. Circular structure for sustainability assessment [40,41].

A triangular structure is another arrangement commonly applied in sustainability assessments, where a number of indicators are aggregated from several criteria to form the base of the triangle, while the criteria are aggregated from each sustainability dimension (Figure 2). Such a structure allows more than two levels of aggregation, and is more suitable for complex assessment with more indicators. It allows traceability and analysis as to how results of each indicator affect the relevant criteria and dimension. This is a widely accepted structure used in sustainability assessments [42] as well as in formulation of sustainability strategies [30].

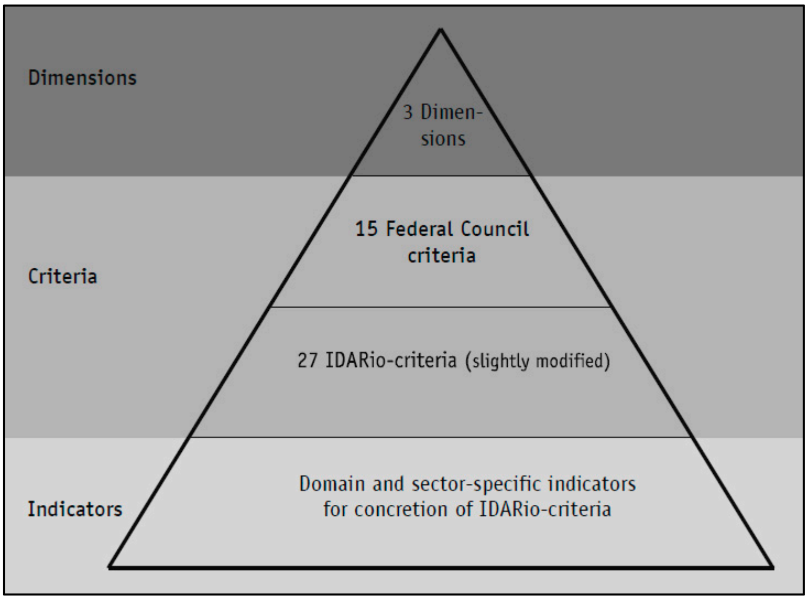

Figure 2. Triangular structure for sustainability assessment [30].

Network structure is applied comparatively less commonly. It is presented in the form of a flow chart or interlinked diagram to incorporate system complexity through modelling interaction among sustainability indicators (e.g., Figure 3) [43]. Network structure is powerful in presenting complex conceptual assessments but is less desired in cases where quantitative results are needed.

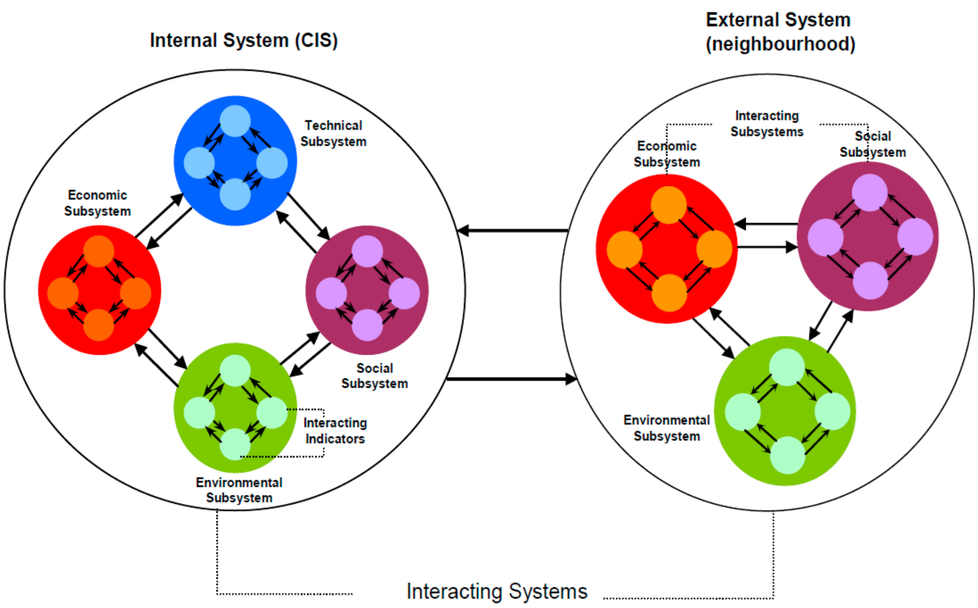

Figure 3. An example of network structure for sustainability assessment [43].

The current sustainability assessment framework thus considers a triangular approach as it is suitable to handle the complexity that is particularly required for the Malaysian palm oil industry to address sustainability challenges including social, economic and environmental objectives as discussed in the previous section.

2.3. Description of the Selected Assessment Framework

The framework of sustainability assessment for crude palm oil production addresses the three principle objectives or dimensions of TBL—environmental, economic and social. The economic objective ensures business sustainability in all the phases of the life cycle of the product or services. The social objective consists of inter-generational and intra-generational equity. The principle of inter-generational equity states that the development must meet the needs of present and future generations. Intra-generational equity, on the other hand, refers to equity in wellbeing (or quality of life) between current generations, concerning human development aspects of sustainable development. The environmental objective focuses on minimizing environmental impacts and resource scarcity throughout the product life cycle. Accordingly, the proposed sustainability framework will assess the social, economic and environmental indicators of the proposed sustainable palm oil production.

The framework is developed based on a strong sustainability concept, where environmental conservation and social equity are of utmost priority. To consider all dimensions of TBL in the assessment and to enable quantitative measurement and easy application, an integrated approach using multi-criteria analysis with indicators/indices is selected. The indicators, criteria and dimensions will be arranged in the triangular structure, similar to the approach followed by IISD (2002) and van Berkel *et al.* (2008) [44,45].

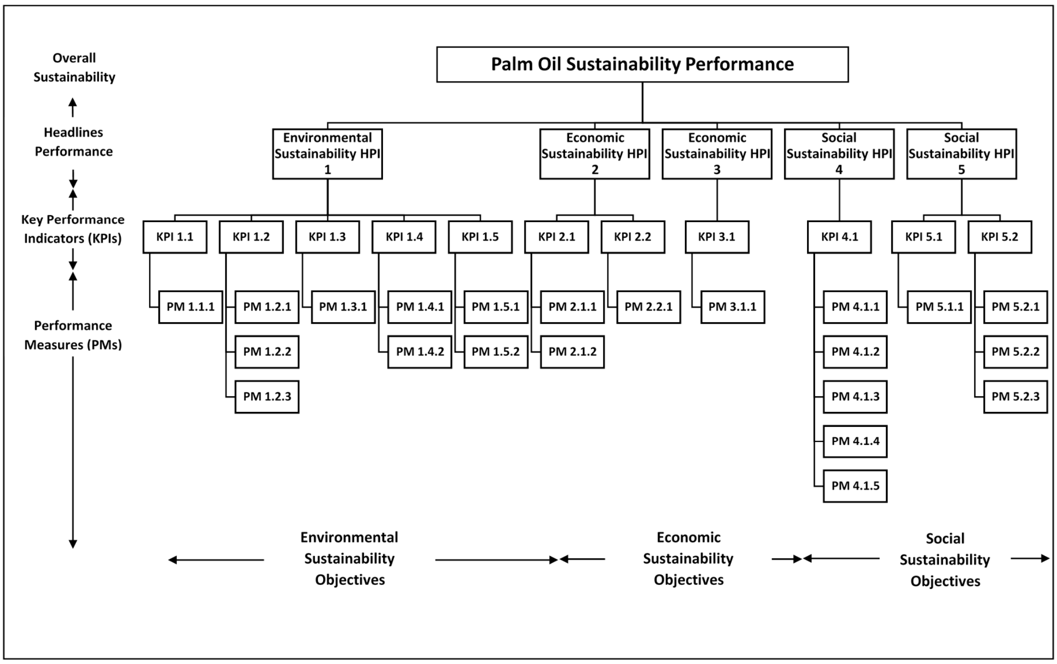

Figure 4. Sustainable palm oil assessment framework [44] (the HPI, KPI and PMs have been numbered for testing purposes in the following section).

The sustainable palm oil assessment framework is as shown in Figure 4. Each TBL objective consists of a number of headline performance indicators (HPI). These indicators are the highest aggregation level for the performance measurement against sustainability objectives. Each HPI is then aggregated into key performance indicators (KPI) which further describe key impact areas of each HPI with respect to palm oil production that could foster or impede the achievement of each sustainability objective. The performance measures (PM), which are the lowest level of aggregation, are established to give quantitative values that could contribute to each KPI [44]. The advantage of using this structure is to enable establishment of specific indicators for field measurements without losing sight of broader sustainability objectives. On the other hand, even though the overall sustainability performance would be assessed under a single umbrella matrix and involve multi-criteria assessment, the framework will ensure that the strong sustainability principles are maintained by openly checking each level of aggregation, and of course by appropriately selecting HPIs, KPIs, and PMs.

2.4. Selection of Indicators: HPI, KPI and PM

As discussed, the HPIs are at the highest aggregation level of performance measures and, hence, should reflect fundamental principles of sustainability. The HPIs are chosen from classic definitions of sustainability and scholarly research on environment, social and economic sustainability.

KPIs are identified from commonly accepted pointers that refer to each HPI. They are nominated after filtering through sustainability reports and literature published by policy makers and researchers. PMs are then selected to address each KPI in the context of palm oil production, referring to palm oil sustainability standards, literature, government authorities' requirements, national statistics, and industrial practices.

There are other means of gathering suitable indicators for sustainability assessment, e.g., a participatory approach that involves substantial participation of stakeholders [46], a valid scientific approach [47], integration in the political process [48], and by interviewing experts [49]. As the main purpose in this paper is to test the feasibility of the sustainability assessment framework, the process of selecting indicators is deliberately simplified through literature review for demonstration purposes.

2.4.1. HPI, KPI and PM for Environmental Sustainability Objectives

According to Brundtland's Report [8], human intervention in the natural system during the course of development must be at a minimum level, not endangering the natural system that supports life on earth. Ekins [50] defines environmental sustainability as "the maintenance of important environmental functions, and hence the maintenance of the capacity of the capital stock to provide those functions". In both definitions, "1. Natural capital conservation" has been seen as an ultimate indicator in determining environmental sustainability. This is also in agreement with the European Commission's basis [51] of their environmental policies and laws, *i.e.*, preservation of natural capital. WWF for Nature, IUCN and UNEP's definition in building strategy of sustainable living, that is to live within the carrying capacity of the supporting ecosystem [52], also presents natural capital as the key important indicator and takes on a "throughput" based approach rather than a "utility" based approach [53]. The former takes into account the bio-physical limit for any development activity while the latter considers the choice of available alternative sources, either fossil or renewable sources, to maintain economic growth.

The natural capital can be categorized into four main aspects [8,50,52,54,55]:

1. Elements, *i.e.*, climate, quality of air, water that contribute to the ecosystem's overall integrity and functions of ecosystem services.
2. Biodiversity, conservation of all species of plants, animals and other organisms.
3. Renewable resources, e.g., soil, forest, cultivated land and fish stocks that replenish at natural rate.
4. Non-renewable resources e.g., fossil fuel and minerals that deplete over time.

Following these four aspects of natural capital, KPIs for environmental sustainability have thus been developed, including "1.1 Climate change", "1.2 Air, water and soil quality", "1.3 Waste generation", "1.4 Biodiversity" and "1.5 Resources consumption". Table 1 shows the performance measures (PMs) for each of these KPIs related to palm oil production.

Table 1. HPI, KPI and PM for environmental sustainability objectives.

Sustainability Objective: Environment					
Headline Performance Indicator 1: Natural Capital Conservation					
Key Performance Indicator		**Performance Measures**		**Ranking Value**	
1.1	Climate Change	1.1.1	GHG Emission	1	> 1 tCO_2eq/tonne CPO
				2	> 0.8 tCO_2eq/tonne CPO
				3	0.5–0.8 tCO_2eq/tonne CPO
				4	< 0.50 tCO_2eq/tonne CPO
				5	< 0.15 tCO_2eq/tonne CPO
1.2	Air, Water and Soil Quality	1.2.1	NOx emission intensity from palm oil mill	1	>400 mg/m^3 emission (continuous)
				2	>350 mg/m^3 emission (continuous)
				3	<350 mg/m^3 emission (continuous)
				4	<200 mg/m^3 emission (continuous)
				5	<100 mg/m^3 emission (continuous)
		1.2.2	Biological Oxygen Demand of water discharged from POME pond	1	>150 mg/L (3 days, 30 degC)
				2	>100 mg/L (3 days, 30 degC)
				3	<100 mg/L (3 days, 30 degC)
				4	<50 mg/L (3 days, 30 degC)
				5	<25 mg/L (3 days, 30 degC)
		1.2.3	Soil Nitrate Level measured through nitrogen in waterway	1	Total nitrogen >300 mg/L
				2	Total nitrogen >200 mg/L
				3	Total nitrogen <200 mg/L
				4	Total nitrogen <100 mg/L
				5	Total nitrogen <50 mg/L
1.3	Waste Generation	1.3.2	% biomass recovery/ recycling	1	<25% recovery
				2	>25% recovery
				3	>50% recovery
				4	>75% recovery
				5	100% recovery
1.4	Biodiversity	1.4.1	Plantation Practice	1	Replacement of forest
				2	Total/large area replanting
				3	Increase heterogeneity through patch planting
				4	Increase connectivity through successive strips/ connectivity
				5	Reduce severity of disturbance through variable rotation
		1.4.2	Land Use	1	Planted on Peat Land/HCVF
				2	Planted on secondary forest/replaced other crops
				3	Replanting on agricultural land
				4	Replanting with Best Management Practice
				5	Replanting with agricultural intensification
1.5	Resources Consumption	1.5.1	Fresh water consumption intensity—Water Footprint	1	> 85 m^3/GJ
				2	>75 m^3/GJ
				3	62 m^3/GJ
				4	<62 m^3/GJ
				5	<50 m^3/GJ
		1.5.2	Fossil fuel consumption intensity (Output/Input energy ratio)	1	<7
				2	<9
				3	9
				4	>10
				5	>12

"1.1 Climate change" has been chosen as one of the KPIs because it could threaten ecosystem functions by causing changes in rainfall distribution, extreme weather, drought, floods, soil–water balance, new pests and diseases [56]. Most importantly, this is one of the key environmental criterion for exporting palm oil to European and North American countries [57,58]. The PM "1.1.1 Greenhouse

Gases (GHG) emissions" predominantly resulting from agriculture and fossil fuel combustion could intensify the natural greenhouse effect and cause temperature rise [59]. The palm oil production involves large scale agricultural activities and milling processes that emit GHGs from fossil fuel combustion, open burning for land clearing [60], decomposition of agricultural waste (*i.e.*, CH_4 emissions) [61,62] and inorganic nitrogen fertilizers' application (*i.e.*, N_2O emissions) [62] that result in the increase of GHG emissions.

"1.2 Air, water and soil quality" together forms a KPI as they are required to achieve a healthy ecosystem. Among the three performance measures which were used in WHO Air Quality Guidelines [63], including airborne particulate matter, Sulfur Dioxide (SO_x) emission intensity and Nitrogen Dioxide (NO_x) emission intensity, "1.2.1 NO_x emission intensity" has been selected as a performance measure as these are pre-dominant air pollutants emitted from palm oil mills' boilers and forest/peatland/ plantation burning for land clearing.

An uncontrolled discharge of Palm Oil Mill Effluent (POME) to the waterway has been gradually increasing the water pollution in Malaysia over the last four decades. The Malaysian Environmental Quality Regulations have since outlined nine indicators and set standards for POME discharge [64]. These indicators are Bio-chemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Solid (TS), Suspended Solid, Oil and Grease, Ammoniacal Nitrogen, Total Nitrogen, pH and Temperature. Among all, "1.2.2 BOD of water discharged from POME pond" has been selected as the performance measure for water quality control in this framework due to its common application and robustness in measuring pollution caused by both organic and inorganic matter [65].

Maintaining organic content and nutrients in soil and controlling soil erosion could assist in maintaining the fertility of agricultural land. Soil quality can be measured in terms of biological, chemical and physical performance [66]. PMs that can be selected for biological attributes are soil respiration and earthworm activity. Physical characteristics of soil quality are measured using soil infiltration, soil bulk density and aggregate stability while soil nitrate level, pH and salt concentration are measured for determining the chemical characteristics of soil [67]. "1.2.3 Soil Nitrate Level" that results from the overuse of N- fertilizer in palm oil plantations to sustain commercial operations has thus been selected as the key PM for soil quality.

In the case of the palm oil production process, a large volume of solid, chemical and biological wastes is generated [68]. Solid waste generation and management are important PMs of environmental control to satisfy both domestic and international standards [59,69]. The biomass solid waste that was generated throughout the milling process is the main concern in the palm oil industry. Whilst palm oil mills apply 3Rs strategies, including reuse, recycle and regeneration for converting these solid waste to resources, there is still a significant amount of this waste that remains unutilized increasing the landfill area. Hence, "1.3.1 Biomass recovery rate" has been considered as one of the key PMs in this study. Chemical wastes which are emitted to the air and water are measured indirectly through air and water quality indicators.

"1.4 Biodiversity" which means the richness of variety of species interacting with each other to establish a stable food chain and to maintain ecological balance [70] is important natural capital for future generations [8]. The PM that is commonly used by biologists for biodiversity is the number of endangered species/number of known species ratio in palm oil plantations and production areas [71]. However, the difficulty associated with data collection for this PM would make it challenging for the palm oil industry to conduct sustainability assessments [72,73]. Hence, "1.4.1 Plantation practice", and "1.4.2 Land-use for plantation", which have direct impact on biodiversity and are easily measured, have been selected as PMs. Land-use pattern (e.g., replantation, farmland replacement), high conservation value (HCV), forest replacement, and plantation on peat land will have different levels of impact on biodiversity [69,74]. Plantation practices that minimise disturbance to existing landscape and create a stable microclimate have also been proven to have different impacts on biodiversity [75].

The other KPI that measures the conservation of natural capital is "1.5 Resources consumption". Renewable resources should be consumed at a rate that the nature could cope with, and if there is sufficient effort in harnessing them. Non-renewable resources are limited and irreversible and, hence, their consumption should be minimised in order to ensure that the resources do not run out before substitutes are available [8,52]. Two major resources, *i.e.*, "1.5.1 Fresh water consumption in terms of water footprint" and "1.5.2 Fossil fuel consumption (Output/Input Energy Ratio)", have been chosen as the PMs for this KPI.

2.4.2. HPI, KPI and PM for Economic Sustainability Objectives

The economic pillar of sustainability is often perceived as monetary income and profit. This perception is narrowly focused. A sustainable economic activity has to remain profitable for a long period of time, in order to be able to "stay in business" [76] and maintain social equity. Whilst monetary value is not the only economic pillar of sustainability, it is something that a business needs to maintain a healthy balance sheet and has the ability to withstand any financial shock to sustain its operation. This is commonly measured as "business continuity and resiliency" in economic studies [77,78].

Besides sustaining the business, economic sustainability has greater depth in its meaning which is to increase productivity potential to "meet human needs" and to "ensure equitable opportunities". The Brundland's report says that sustainable development requires a change in the content of growth rather than growth itself [8]. Economic growth shall also bring upon positive changes to the society in meeting its essential needs, and empower the community with an ability to change their lives.

"2. Business continuity and resiliency" and "3. Sharing of economic power" are thus chosen as two HPIs to be achieved under this sustainability objective.

The HPI entitled "2. business continuity and resiliency" is directly related to the KPI "2.1 Production efficiency". Increasing productivity not only has financial benefits, it also conserves the natural resources for the present and future generations. In the case of crude palm oil production, the PMs during the plantation (or on-farm) and milling stages would be the "2.1.1 Plantation Yield" *i.e.*, Fresh Fruit Bunches (FFB) harvested per hectare, and "2.1.2 Mill production efficiency", *i.e.*, the amount of crude palm oil produced per tonne of FFB, respectively.

The second KPI, "2.2 Business Continuity", is the "capability of the organization to continue delivery of products or services at acceptable predefined levels following a disruptive incident" [77]. It reflects how consistently the crude palm oil production is profitable. Sustainable Growth Rate (SGR) presents how the economic growth can be maintained without increasing its financial leverage [79]. In the case of the palm oil industry, an attainable growth rate would mean that a plantation could remain profitable and ensure security of supply, without increasing its debts, even under circumstances where the crude palm oil price plunges. The deviation of actual growth rate from SGR reflects the financial viability of a business. Therefore, "2.2.1 Actual Growth Rate" measuring against SGR has been chosen as a PM over profit margin.

One of the objectives of sustainable development is to enhance intra-generational equity by reducing the gap between rich and poor [8]. The HPI "3. Sharing of economic power" will be measured by the KPI "3.1 Relative poverty", which is measured at 50% of the national median income [80]. Relative poverty would be a more useful KPI than the absolute poverty level (a fix income value is set as the poverty line) to capture the distribution of wealth [81]. This is because the relative poverty line that is set at RM2292.50 (half of the average income per person per month in Malaysia for the year of 2014) (1 USD = RM3, 2014) reflects the imbalance in wealth distribution. About 46.6% of the wealth is shared by the top 20%, 36.9% is shared by the middle 40%, while only 16.5% is shared by the bottom 40% in Malaysia in 2014 [82]. In the case of the absolute poverty line (RM860 per month in 2014), only less than 1% of Malaysians live under the poverty line. This does not represent a detailed breakdown of wealth distribution or wider social inequality. In case of palm oil production, the PM is "3.1.1 Average annual income per workers", and it is measured against the national median income that determines the relative poverty level.

The HPI, KPI and PM for the economic sustainability objectives are as presented in Table 2.

Table 2. HPI, KPI and PM for economic sustainability objectives.

Sustainability Objective: Economy					
Headline Performance Indicator 2: Business Continuity and Resiliency					
Key Performance Indicator		**Performance Measures**		**Ranking Value**	
2.1	Production efficiency	2.1.1	Plantation yield	1	<16 tonne per ha
				2	< 17 tonne per ha per year
				3	19 tonne per ha per year
				4	>19 tonne per ha per year
				5	>20 tonne per ha per year
		2.1.2	Mill production efficiency	1	<0.20 tonne CPO per tonne FFB
				2	<0.21tonne CPO per tonne FFB
				3	0.21 tonne CPO per tonne FFB
				4	>0.21 tonne CPO per tonne FFB
				5	>0.22 tonne CPO per tonne FFB
2.2	Business continuity	2.2.1	Actual Growth Rate	1	>15% deviation from Sustainable Growth Rate
				2	15% deviation from Sustainable Growth Rate
				3	10% deviation from Sustainable Growth Rate
				4	5% deviation from Sustainable Growth Rate
				5	0% deviation from Sustainable Growth Rate
Headline Performance Indicator 3: Sharing of Economic Power					
Key Performance Indicator		**Performance Measures**		**Ranking Value**	
3.1	Relative Poverty	3.1.1	Average annual income per worker	1	<25% of national median income
				2	<50% of national median income
				3	⩾50% of national median income
				4	>75% of national median income
				5	⩾100% of national median income

2.4.3. HPI, KPI and PM for Social Sustainability Objectives

The aim of sustainable development is to meet the basic needs of life of current and future generations [8]. In order for this to happen, seven critical basic needs, including jobs, food, healthcare, water, sanitation and shelter, are to be fulfilled. A livelihood should be created to empower households in the local community that could be affected by palm oil plantation. "4. Social Wellbeing" has thus been selected as one of the HPIs that will be achieved under the social sustainability objective. This HPI has "4.1 Meeting essential human needs" as one of its KPIs, which have five PMs including "4.1.1 Employment opportunity for the local", "4.1.2 Workers' accessibility to water supply", "4.1.3 Workers' accessibility to healthcare", "4.1.4 Provision of sanitation facilities to workers", and "4.1.5 Provision of housing facilities to workers" (Table 3).

Table 3. HPI, KPI and PM for social sustainability objectives.

Sustainability Objective: Social					
Headline Performance Indicator 4: Social Wellbeing					
Key Performance Indicator		**Performance Measures**		**Ranking Value**	
4.1	Meeting Essential Human Needs	4.1.1	Employment opportunity for the local	1	<25% local employment
				2	⩾25% local employment
				3	>50% local employment
				4	>75% local employment
				5	100% local employment
		4.1.2	Workers' accessibility to water supply	1	<25% accessible to portable water
				2	>25% accessible to portable water
				3	>50% accessible to portable water
				4	>75% accessible to portable water
				5	100% accessible to portable water

Table 3. *Cont.*

Sustainability Objective: Social					
Headline Performance Indicator 4: Social Wellbeing					
Key Performance Indicator		**Performance Measures**		**Ranking Value**	
4.1	Meeting Essential Human Needs	4.1.3	Workers' accessibility to healthcare	1	<25% accessible to healthcare facilities
				2	>25% accessible to healthcare facilities
				3	>50% accessible to healthcare facilities
				4	>75% accessible to healthcare facilities
				5	100% accessible to healthcare facilities
		4.1.4	Provision of sanitation facilities to workers	1	<25% accessible to sanitation facilities
				2	>25% accessible to sanitation facilities
				3	>50% accessible to sanitation facilities
				4	>75% accessible to sanitation facilities
				5	100% accessible to sanitation facilities
		4.1.5	Provision of housing facilities to workers	1	<25% provision to housing facilities
				2	>25% provision to housing facilities
				3	>50% provision to housing facilities
				4	>75% provision to housing facilities
				5	100% provision to housing facilities
Headline Performance Indicator 5: Social Equality					
Key Performance Indicator		**Performance Measures**		**Ranking Value**	
5.1	Equal opportunity to the poor	5.1.1	Smallholders' equity	1	<25% of CPO sourced from smallholders
				2	>25% of CPO sourced from smallholders
				3	>50% of CPO sourced from smallholders
				4	>75% of CPO sourced from smallholders
				5	100% of CPO sourced from smallholders
5.2	Local community empowerment and engagement	5.2.1	Access to information and knowledge	1	No information available
				2	Information available but local community are not informed
				3	Local community informed prior to the plantation and mill development
				4	Local community informed periodically on the plantation and mill development
				5	Local community are timely updated
		5.2.2	Community involvement in decision making	1	No involvement at all
				2	Indirect communication channels are available
				3	Local community could provide feedback to plantation owner/mill management through establish channel
				4	Local community has representation in plantation/mill HSE Committee
				5	Consensus from local community is mandatory for any decision that impact them
		5.2.3	Level of community acceptance to plantation and mill activities	1	<25% agreement from community
				2	<50% agreement from community
				3	>50% agreement from community
				4	>75% agreement from community
				5	100% agreement from community

In addition to "Social Wellbeing", "Social Equality" is another intra-generational equity aspect for providing equal distribution of opportunity and wealth, where no specific group is marginalised [8]. Communities that could potentially be affected by palm oil plantation include employees, small-landholders and even the neighbouring communities, as they have various perspectives, consumption patterns and lifestyles and interests [3]. Social equality would vary and depend on how much the local community is empowered through a number of ways, such as consultation, engagement and employment creation.

"5. Social Equality" has thus been considered as the second HPI and one of the KPIs is "5.1 Equal opportunity to the poor". It measures how much the economic benefits of palm oil industries are shared by the local small farmers contributing to this industry. The price of crude palm oil (CPO) has been considered fixed by the market, hence the PM refers to "5.1.1 Smallholders' equity", *i.e.*, the percentage of CPO sourced from small farmers compared to large plantations.

Beyond "equal opportunity", "5.2 Local community empowerment and engagement" is another KPI that needs to be considered. An empowered community has the attributes of confidence, inclusiveness, organisational ability, cooperation and ability to influence [83]. A community gains confidence through education, training and practice. A community would also be more co-operative if its voices are heard and disseminated via organised channels. The industry–community relations would be strengthened if the community could be involved in collective decision making in matters that affect them. The PMs that indicate the level of local community empowerment and engagement are identified as "5.2.1 Access to information and knowledge", "5.2.2 Community involvement in decision making", and "5.2.3 Level of community acceptance to plantation and mill activities".

3. Testing the Framework

3.1. Five-level Ranking System & Development of Benchmarking Criteria

The PMs are assessed using a Likert scale of 1–5, depending on the performance of palm oil production under environmental, economic and social conditions. Levels 1, 3 and 5 represent the poorest performance, the threshold value, and the ideal performance, respectively. The performance at different levels of ranking is pre-defined for every PM as shown in Tables 1–3.

Threshold value in this framework is defined as "a minimal level of performance that is acceptable as environmentally, economically or socially sustainable in Malaysia's context". The threshold values are determined through the review of legislative requirements, international environmental commitment, technological constraints, and published literature in the journal articles. Criteria used in selecting the threshold values for PMs, in the order of preference, are as below:

a. Values that are considered ecologically and socially sustainable from the Malaysian context, and are obtained from literature research, multidimensional analysis and system modelling.
b. Values that meet the national target set by the International Treaties.
c. Values that meet relevant Malaysian legislative requirements.
d. Average oil crop performance value as that will provide a benchmark for oil palm production, compared with other competing oil crops in the world.
e. Optimum palm oil plantation performance value in the context of Malaysian plantations considering the fact that yield could vary with soil types and farming practices in different agro-ecological and hydrological zones across the country.
f. Best possible performance values of existing technology (*i.e.*, palm oil mill) that is available in the Malaysian market.

Once these threshold values are selected, they will be cross checked or verified through experts' opinions, and must comply with the international standards.

The PMs that are currently applied are "1.2.1 NOx emission intensity" and "1.2.2 Biological Oxygen Demand of POME discharged from palm oil mills" and "1.2.3 Soil Nitrate Level in waterway". The threshold values of these PMs were set to meet the requirements of Malaysian regulations for Environmental Quality (Clean Air Act 2014 and Crude Palm Oil 1977) [84]. Ranking values of 1, 2, 4 and 5 are set for each PM at an evenly distributed scale around a threshold value that measures the sustainability performance of palm oil production.

Experts' opinions that were published in the refereed literature have also been considered in determining both threshold values and other values in the Likert scale for ranking purposes. The values for ranking for PMs on "1.4.1 plantation practice" and "1.4.2 land use" have been developed on the basis of the relevant studies carried out by Luskin *et al*. [75] on microclimate and habitat heterogeneity through the oil palm lifecycle. Based on the study, the ranking values for the Likert's scale (*i.e.*, from high to low) for the impact of plantation practice on biodiversity would be total replacement of forest (1), total/large area of replanting (2), patch planting (3), successive strips/connectivity (4) and variable rotation (4) [75]. Likewise, the threshold value for PM of "1.5.2 fossil fuel consumption intensity (energy ratio of palm oil production/fossil fuel consumption)" has been considered as 9 through the review of both local and international literature that were published recently or at least within the last five years [85].

Multidimensional perspective, *i.e.*, analysis on the threshold value based on multiple input factors has also been considered for some PMs in determining the ranking and threshold values. For example, "1.1.1 GHG emission" can be measured in a number of ways, including absolute GHG emission in ppm, absolute GHG emission in CO_2eq/ha or per tonne CPO per year or relative GHG emission (CO_2eq/kWh) to fossil fuel. To set the correct target value and threshold value, the question is raised as to whether Malaysia is committed to a 2 °C reduction target [86], or what is the maximum allowable GHG emissions per tonne of CPO per year. Malaysia's agreement in the Copenhagen Summit is to achieve a GHG reduction in 2020 of 40% of the 2005 level [87].

The total GHG emission level for Malaysia in 2005 was 279.2 MtCO_2eq while total GHG removal level (sink) was 240.5 MtCO_2eq which takes into account all activities including land use changes, and deforestation [80]. With a commitment to achieving a 40% GHG reduction target by 2020, the total allowable emissions in 2020 would be 167.52 MtCO_2eq/ year. Around 4% [2] of these GHG emissions result from agricultural activity (including palm oil production), and so the targeted total emissions level from palm oil production would be 6.7 MtCO_2eq/year in 2020 (average reduction of 0.3 MtCO_2eq/year over 15 years). Using the 2014 palm oil production volume of 48,398,384 tonne CPO [88], the targeted emissions level per tonne of CPO would be 0.138 tCO_2eq/ tonne CPO/year by 2020 if the annual production volume remains the same over this period. This value is set as the best case scenario—the ranking value of 5 has been allocated to this GHG value. The threshold has been considered as 0.5–0.8 tCO_2eq/tonne CPO/year as this value is achievable given current technological and socio-economic constraints [88]. The GHG per tonne CPO of yield was 3.2–4 tonne per hectare is 920–2007 kgCO_2eq (0.920–2.007 tCO_2eq) in 2009, which does not include carbon stock change associated with sequestration and peat emission [89]. Malaysian Palm Oil Board (MPOB) published data in 2010 shows that GHG emissions per tonne CPO were 970.58 kgCO_2eq without taking into account the capture of biogas and 505.76 kgCO_2eq with biogas capture (0.5–0.97 tCO_2eq), but none of them included carbon stock change effects [64].

Ideally, the threshold values shall be referred to as only those values which are considered ecologically and socially sustainable from Malaysia's context, and they were obtained from literature review, analysis and system modelling. However, this is constrained by the availability of literature, and also the complexity of system modelling for every PM for palm oil production in Malaysia. Hence, in some cases, the threshold values for PMs are determined using the average performance of oil crops or palm oil industries. This gives a justification as to where the palm oil production stands, as compared to other options for food and renewable energy.

The average value indirectly represents the performance constrained by geological factors, existing technology and practices [90]. It also helps compare the performance of one production system with other feasible options in the market. For example, "1.5.1 fresh water consumption/ water footprint" threshold value has been determined as 62 m^3/GJ, which is the average water footprint values obtained from 15 different oil crops planted in a country with tropical weather [91]. "2.1.1 Plantation yield" and "2.1.2 Mill production efficiency" have been considered as PMs for the economic sustainability objective. The threshold value of "2.1.1 plantation yield" has been considered as 19 tonne/ha/year on the basis of optimum performance by the Malaysian palm oil industry recently in the year 2014, while the threshold value for "2.1.2 mill production efficiency" is set at 0.21 tonne CPO/tonne FFB, considering the best performance of the available existing technology in the industry.

3.2. Performance Measure Calculation Formula

Once the ranking level of each performance measure is determined, the performance for KPI, the following formulae have been developed in this research to calculate HPI and then sustainability objectives.

- The performance of each KPI = the average ranking of PMs related to it.

$$Performance\ of\ KPI\ 1.1 = \frac{\sum PM1.1.1 + PM1.1.2 + \ldots + PM1.1.n}{n} \tag{1}$$

where, 1.1.1, 1.1.2, . . . , 1.1.n represents score for first PM, second PM and nth PM of KPI 1.1.

- Performance of each HPI = average performance of related KPIs.

$$Performance\ of\ HPI\ 1 = \frac{\sum KPI\ 1.1 + KPI\ 1.2 + \ldots + KPI\ 1.n}{n} \tag{2}$$

where, 1.1, 1.2, . . . , 1.n represents score for first KPI, Second KPI and nth KPI of HPI 1.

- Overall sustainability performance = the average ranking of HPIs related to all three triple bottom line objectives.

$$Overall\ Sustainability\ Performance = \frac{\sum HPI\ 1 + HPI\ 2 + \ldots + HPI\ n}{n} \tag{3}$$

where, 1, 2, . . . , n represents score for first HPI, Second HPI and nth HPI of respective sustainability objective.

4. Results

The sustainability assessment framework has been tested for the crude palm oil production in the Malaysian palm oil industry. The score of each PM for triple bottom line objectives has been measured using Equations (1)–(3) (Table 4). Since no field data has been collected yet for this research, the national statistics of the year 2014–2015 and other relevant literatures as cited in Table 4 have been reviewed to find out the generic values of PMs of existing palm oil practices at the national level to compare with the threshold values for testing this framework. In the case of implementation of this framework, the real data from a palm oil industry will be collected for its sustainability assessment.

Utilizing the equations in Section 3.2 and ranking values of PMs in Table 4, the KPIs and HPIs of three sustainability objectives have thus been calculated (Table 5).

Table 4. Score for PM and its justification.

	Performance Measures	Score for PM	Justification and Reference
			Environmental Sustainability Objective
1.1.1	GHG Emission	2	87% mill in Malaysia do not have biogas facilities. Thus most of the production system has GHG emission around 0.97 tCO_2/tonne CPO [13]
1.2.1	NOx emission intensity from palm oil mill	3	It is assumed that meeting the regulation requirement is mandatory
1.2.2	Biological Oxygen Demand of water discharged from POME pond	3	It is assumed that meeting the regulation requirement is mandatory
1.2.3	Soil Nitrate Level measured through pH in waterway	3	It is assumed that meeting the regulation requirement is mandatory
1.3.2	% biomass recovery/recycling	2	Palm oil mill mass balance shows that >50% of biomass produced goes to Palm Oil Mill Effluent (POME). For mill without biogas capture, biomass recovery will be <50% and majority of mill in Malaysia do not have an anaerobic digester to generate biogas
1.4.1	Plantation Practice	2	Large plantations in Malaysia commonly practice large area replantation [75]
1.4.2	Land Use	2	Largest portion of land-use change for palm oil plantation happened during 1990–2006, and 42% are from rubber plantation conversion [64]
1.5.1	Fresh water consumption intensity—Water Footprint	2	Palm oil water footprint is recorded as 75 m^3/GJ [91]
1.5.2	Fossil fuel consumption intensity (Output/Input energy ratio)	3	Fossil fuel consumption for palm oil production or fossil fuel intensity (Output $_{\text{energy of oil produced}}$/Input $_{\text{energy of fossil fuel consumed}}$) is recorded as 9 in 2014 [85]
			Economic Sustainability Objective
2.1.1	Plantation yield	3	Refer to Malaysian average FFB yield per ha per year for 2014, *i.e.*, 18.63 [88]
2.1.2	Mill production efficiency	2	Refer to MPOB statistic 2014, Oil extraction rate in average for palm oil mill is 20.62% [88]
2.2.1	Actual Growth Rate	3	Ideal condition with score of 5 would be zero deviation from sustainable growth rate. Growth rate is very much dependent on specific supply chain economic performance. Thus for overall evaluation it is assumed at 3 with 10% deviation
3.1.1	Average annual income per worker	1	Malaysia median income in 2014 is RM4585 [92]. Thus, relative poverty line refer to household income ⩽50% of RM4585, *i.e.*, ⩽RM2292.50. Malaysia oil palm plantation workers is earning average of RM900 as reported by Reuters [93], way below the relative poverty line

Table 4. *Cont.*

	Performance Measures	Score for PM	Justification and Reference
	Social Sustainability Objective		
4.1.1	Employment opportunity for the local	1	Oil palm plantations' foreign workers employment as of 2014 is as high as 75.9% in Malaysia [94]
4.1.2	Workers' accessibility to water supply	5	Workers for plantation and mill in Malaysia are supplied with portable water [3]
4.1.3	Workers' accessibility to healthcare	5	Workers for plantation and mill in Malaysia are supplied with healthcare access [3]
4.1.4	Provision of sanitation facilities to workers	5	Workers for plantation and mill in Malaysia are supplied with sanitation facilities [3]
4.1.5	Provision of housing facilities to workers	5	Workers for plantation and mill in Malaysia are supplied with housing facilities [3]
5.1.1	Smallholders' equity	2	Smallholders contribute to 35%–45% of CPO production as in 2015 [95]
5.2.1	Access to information and knowledge	1	Plantation and mills are not required to provide information to the local community under existing legislation. The usual practice is that most industries do not necessarily feel obliged to engage the neighbouring community [96]
5.2.2	Community involvement in decision making	2	Local community has no power or access to decision making in any neighbouring plantation or mill. Indirect communication will be made through area community leaders
5.2.3	Level of community acceptance to plantation and mill activities	1	Local community agreement or opinion is not a requirement in Malaysia for plantation/mill construction and their daily production activities [97]

Note: 1. For PM 1.2.1, 1.2.2 & 1.2.3, instead of an answer of "yes" or "no" in compliance to regulatory requirement, regulatory requirement level is set as threshold value (score of 3), while other scores (1,2, 4 and 5) reflect how much worse/ better the plantation/ mill is performing from the regulatory requirement. For this exercise, it is assumed that meeting regulatory requirement is mandatory; hence, the plantations and mills in this evaluation meet the threshold value. 2. Elements of calculation for Actual Growth Rate include profit, debts to equity ratio, dividend payout and assets value. Thus, it is very specific to each mill/ plantation financial condition. Thus score at threshold value is selected in this evaluation. 3. The data obtained from Malaysian Statistics for Median Income only considers the monetary income. Hence, income provided "in kind" to palm oil plantation workers, e.g., housing, healthcare, water supply is not considered in order to make a fair comparison.

Table 5. Overall assessment results.

Sustainability Objectives		Headline Performance Indicator	Key Performance Indicator		Performance Measures		Score for PM	Score for KPI	Score for HPI	Score for Sustainability Objective	Score for Overall Sustainability
Environment	1	Natural Capital Conservation	1.1	Climate Change	1.1.1	GHG Emission	2	2.00	2.30	2.30	2.37
			1.2	Air, Water and Soil Quality	1.2.1	NOx emission intensity from palm oil mill	3	3.00			
					1.2.2	Biological Oxygen Demand of water discharged from POME pond	3				

Table 5. *Cont.*

Sustainability Objectives	Headline Performance Indicator		Key Performance Indicator		Performance Measures		Score for PM	Score for KPI	Score for HPI	Score for Sustainability Objective	Score for Overall Sustainability
Environment	1	Natural Capital Conservation	1.2	Air, Water and Soil Quality	1.2.3	Soil Nitrate Level measured through pH in waterway	3	3.0	2.30	2.30	2.37
			1.3	Waste Generation	1.3.2	% biomass recovery/recycling	2	2.00			
			1.4	Biodiversity	1.4.1	Plantation Practice	2	2.00			
					1.4.2	Land Use	2				
			1.5	Resources Consumption	1.5.1	Fresh water consumption intensity—Water Footprint	2	2.50			
					1.5.2	Fossil fuel consumption intensity (Output/Input energy ratio)	3				
Economy	2	Business Continuity and Resiliency	2.1	Productivity efficiency	2.1.1	Plantation yield	3	2.50	2.75	1.88	
					2.1.2	Mill production efficiency	2				
			2.2	Business Continuity	2.2.1	Actual Growth Rate	3	3.00			
	3	Sharing of Economic Power	3.1	Relative Poverty	3.1.1	Average annual income per worker	1	1.00	1.00		
Social	4	Social Well-being	4.1	Meeting Essential Human Needs	4.1.1	Employment opportunity for the local	1	4.20	4.20	2.93	
					4.1.2	Workers' accessibility to water supply	5				
					4.1.3	Workers' accessibility to health care	5				
					4.1.4	Provision of sanitation facilities to workers	5				
					4.1.5	Provision of housing facilities to workers	5				
	5	Social Equality	5.1	Equal opportunity to the poor	5.1.1	Smallholders' equity	2	2.00	1.67		
			5.2	Local community empowerment and engagement	5.2.1	Access to information and knowledge	1	1.33			
					5.2.2	Community involvement in decision making	2				
					5.2.3	Level of community acceptance to plantation and mill activities	1				

5. Discussion

The sustainability assessment results as presented in Table 5 and Figures 5–8 show that the sustainability performance score of Malaysian crude palm oil production is 2.37 out of 5, which is below the threshold value of 3. The score of economic sustainability objectives is the lowest (1.88) which pulls down the overall sustainability performance of the crude palm oil production. In addition, the scores of environmental (2.30) and social (2.93) objectives are also below the threshold values. This framework thus enables identifying PMs (or "hotspots") requiring major improvements for achieving the required level of sustainability performance.

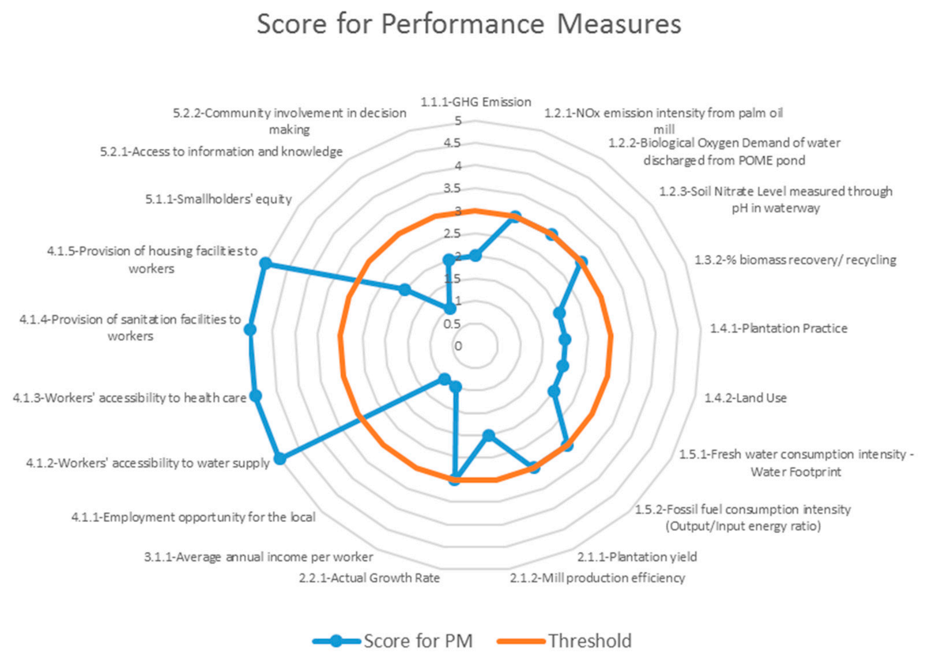

Figure 5. Score for performance measures.

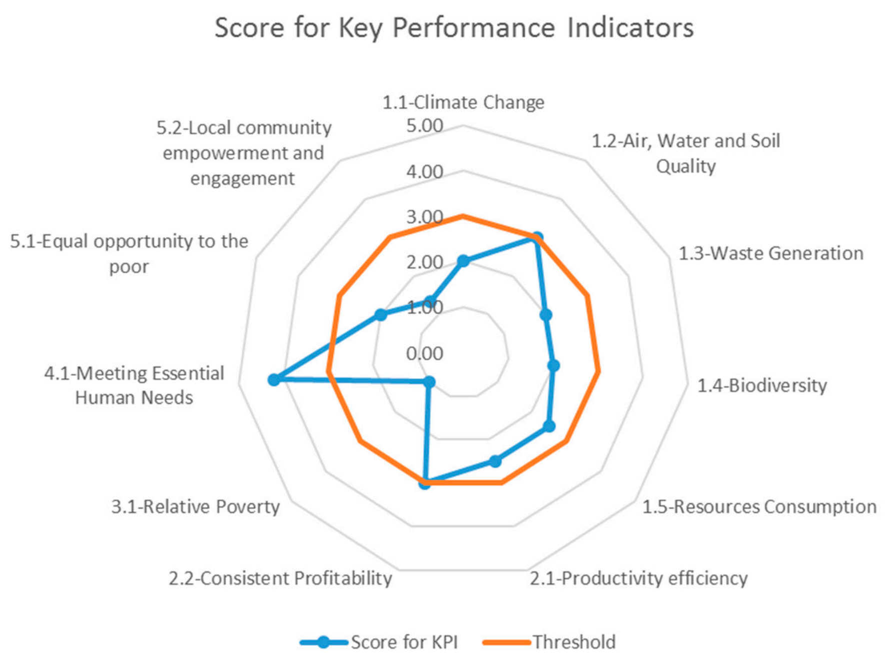

Figure 6. Score for key performance indicators.

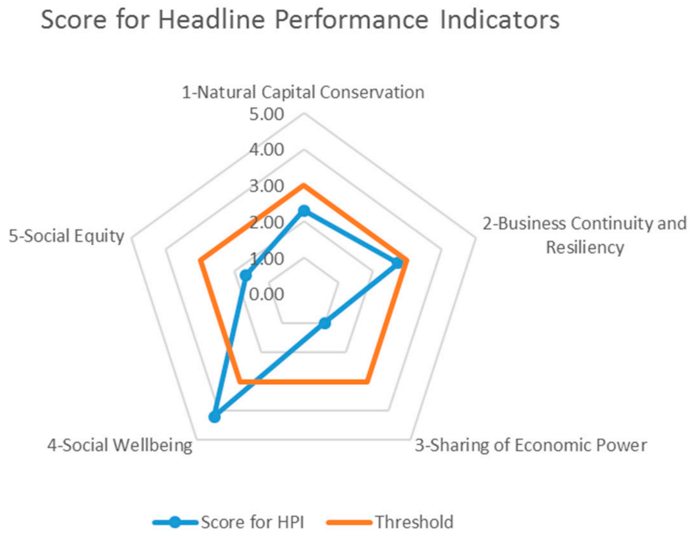

Figure 7. Score for headline performance indicators.

Figure 8. Score for sustainability objectives.

One of the "hotspots" identified is the "3.1.1 Average income per worker", which has resulted in the increase of relative poverty and thus decreased the HPI for "3. Sharing of economic power" under the economic sustainability objective. The second hotspot is "4.1.1 Employment opportunity for the local people". The local employment opportunity has been reduced due to replacement of local manpower with cheap foreign labour from neighbouring developing countries [94]. This will reduce the score of the KPI for "4.1 Meeting essential human needs" for livelihood, as the the score of HPI for "4. Social well-being". However, by improving the wellbeing of workers in terms of providing the employees (both foreigners and locals) with decent housing, access to water, sanitation and healthcare facilities, particularly for those working in remote plantation and mills [3], the scores for relevant KPIs and HPIs can be increased. The third and fourth hotspots are "5.2 Local community empowerment and engagement" where the KPI score (1.33) is relatively low and hence reduces the score for "5. Social equality" HPI. This is because of the fact that the sharing of information and exchange of knowledge between industry and the local community is not common practice in Malaysia [98].

Interestingly, no hotspot has been identified under the environmental sustainability objective, but it does not necessarily mean that the performance of this objective is satisfactory. Out of nine environmental PMs, five PMs are at level 2, which is below the threshold value, but the scores of the remaining 4 PMs are so high that it pulled up the overall score for environmental sustainability above the threshold value. Other performance measures are controlled reasonably well because they are performances regulated by Malaysian authorities. Incompliance with the threshold values for these performance measures would mean risk of facing legal action, halting operations or even losing business licenses.

Therefore, this framework will not only assess the sustainability performance of palm oil production in Malaysia but it will also help in selecting appropriate strategies for addressing the identified PMs for restructuring the supply chain of CPO production to improve sustainability. The hotspots identified, the causes of these hotspots and relevant opportunities for improvement for addressing these hotspots have been presented in Table 6.

We have identified the following advantages in developing a sustainability assessment framework:

- It allows integration of all three sustainability dimensions into one single score, thus providing an opportunity to compare the sustainability performance of similar products.
- It allows the application of a triangular structure approach of sustainability assessment by integrating Key Performance Indicators and Performance Measures into Higher Performance Indicators.
- It is flexible in adapting to both quantitative and qualitative measures by interpreting these measures into indices.
- The integrated, multi-criteria analysis approach allows sustainability objectives to be assessed in a balanced and integrated manner. A clearly defined, quantitative PM criteria and presentation of results at different levels of aggregation would also allow such assessment to be more transparent.
- The hotspots could be easily identified through this assessment process and the remediation or relevant improvement strategies can specifically be devised accordingly.
- It could be a decision making tool for policy makers, growers and producers to identify strategies for further improvement and achieving sustainability objectives. This is because the stakeholders would be able to identify areas of weakness from the assessment results, and would be able to make an effective determination as to how well they are performing from the threshold and best practice, and work towards all three sustainability objectives.
- The framework could offer flexibility as the ranking values could be reviewed from time to time as technology advances, policies changes, or regulations are revised.

Some weaknesses observed from this assessment framework are as discussed below:

- As the Likert scale is equally applied to all PMs, the relative advantages and disadvantages between PMs are not clearly differentiated. For example, the employment opportunity for the local people is an important hotspot, but it does not have much influence on the KPI and HPI as the remaining PMs of the KPI and HPI perform well.
- Another aspect is, due to a variable number of performance measures for each sustainability objective, *i.e.*, nine for environment, four for economy and nine for social objectives, it can be observed that each PM under economic sustainability carries a heavier weighting. Non-performance of a single performance measure under the economic sustainability objective would be highly sensitive to the KPI, HPI and overall sustainability, compared to performance measures under environment and social sustainability.
- Threshold values for some PMs (e.g., "1.5.1 Fresh water consumption intensity—Water Footprint" and "1.5.2 Fossil fuel consumption intensity (Output/Input energy ratio)") refer to average/ best industrial practices, which might be still too high for the natural system, e.g., groundwater replenishment, fossil fuel resources, to accommodate. The use of such PMs causes deviation from the concept of strong sustainability, where the performance shall be judged objectively, solely by its impact on society and the environment.

Table 6. Hotspots, their reasons and opportunities for improvement.

	Hotspots	Reason	Opportunities for Improvement
1.	3.1.1 Average annual income per worker	• Minimum wage in Malaysia is set too low, way below the relative poverty line. • Most of the workers are foreign workers, who do not have much bargaining power for negotiation with the employer.	• The minimum wage shall be reviewed. • Use of skilled workers and technicians shall be encouraged instead of relying on general labour. • Standard wage policy needs to be applied by the government
2.	4.1.1 Employment opportunity for the local people	• The local people do not want to work in the plantation due to hardship and low wages. • Large plantation employer would prefer the foreign workers who are willing to work for lower wages to keep the business competitive.	• The nation's policy in importing foreign workers shall be reviewed. • The model of large plantation with high demand on foreign labour could be replaced with smallholder schemes to encourage more local farmers/entrepreneurs. • Government's incentives on education, training, effort reducing technologies and health and safety as it is one of nation's key industries.
3.	5.2.1 Access to information and knowledge	• There is no regulatory requirements for industry to share information with the community. • It is not a common culture in Malaysia for industry to share information and knowledge with the local people.	• Sharing of information and knowledge between plantations and mills with the local people shall be made a good practice by the authority. • Organising workshops at local level participated by all stakeholders including government, NGOs, industries and the local community
4.	5.2.3 Level of community acceptance to plantation and mill activities	• There is no regulatory requirements for industry to obtain permissions or consensus from the local community in any phase of the development .	• Consensus of the local community shall be made a mandatory requirement prior to any development approval by the authority.

6. Recommendations

Considering different degrees of importance for each indicator under different environmental situations, policy changes and socio-economic conditions, relevant weightings could be applied for HPIs, KPIs and PMs. The weightings for an indicator could be discerned through stakeholder consultations, workshops involving people directly and indirectly related to palm oil production. The following formula could be applied to determine weightings:

$$Performance\ of\ HPI\ 1 = \frac{\sum W1KPI\ 1.1 + W2KPI\ 1.2 + \ldots + WnKPI\ 1.n}{W1 + W2 + \ldots + Wn} \quad (4)$$

where W1, W2, ... , Wn represents weighting factor applied to KPI 1.1, KPI 1.2, and KPI 1.*n* respectively

$$Performance\ of\ KPI\ 1.1 = \frac{\sum W1PM\ 1.1.1 + W2PM1.1.2 + \ldots + WnPM1.1.n}{W1 + W2 + \ldots + Wn} \quad (5)$$

where W1, W2, ... , Wn represents weighting factor applied to PM 1.1.1, PM 1.1.2, and PM 1.1.*n* respectively.

With this amendment, the influence of important performance measures and indicators would not be overlooked in the results of higher level indicators (*i.e.*, HPIs). Secondly, the current analysis suggests that an equal number of PMs needs to be developed for each of these three sustainability objectives, or a weighting factor could be applied to the PM in a way that the results of KPI and HPI could better reflect the actual scenario. The introduction of weighting factors, however, does not intend to offset the impact of sustainability performance measures, or to give precedence to socio-economic development. It shall be applied carefully, referring to scientific findings and diverse stakeholders' input to avoid shifting from strong sustainability objectives to weak sustainability objectives.

It is also suggested that a thorough literature review is carried out and separate system modelling is undertaken to identify threshold values that are considered ecologically and socially sustainable for every PM. That could further verify if targets set according to the latest legislative requirements and international treaties are legitimate and applicable. It would also ensure that the assessment framework has incorporated strong sustainability principles.

7. Conclusions

The proposed sustainability assessment framework for crude palm oil production has been developed to overcome the weaknesses in some of the existing assessment methods. It is aimed at developing a holistic, comprehensive, measurable, and easy to apply approach or framework, thus providing a quick self-assessment tool for the industries in the palm oil supply chain. The testing of the framework by utilizing existing data on Malaysian crude palm oil production in general reflects the sustainability performance of the industry. The assessment framework has been successfully tested and it was found that there are still opportunities for improvement in this current framework by selecting appropriate weightings of PMs, introducing an equal number of PMs for each sustainability objective and by using more scientific threshold values.

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Appendix 3 – Paper 3

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Statement of Contribution

To Whom It May Concern,

I, Chye Ing LIM, contributed to literature review, methodology development, hypothetical data collection, results analysis, discussion and writing (80%) of the paper/publication entitled:

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The remaining 20% of this paper/ publication was contributed by Wahidul K. Biswas.

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I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

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ORIGINAL PAPER

Development of triple bottom line indicators for sustainability assessment framework of Malaysian palm oil industry

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Abstract The production of crude palm oil has environmental, economic and social implications. A sustainability assessment framework is needed to improve the sustainability performance of crude palm oil production in a carbon-constrained economy. The objective of this paper is to develop Performance Measures for triple bottom line assessment in the Malaysian palm oil industry, which includes Key Performance Indicators and Higher Performance Indicators for implementing the sustainability assessment framework. The Performance Measures of the triple bottom line assessment were built on the framework of Lim and Biswas (Sustainability 7(12):16561–16587, 2015). The measures were further developed through a participatory approach involving stakeholders and area experts, including Government, Industry, Academia and Local Smallholders/Non-Government Organisations. The developed framework presents a final list of Performance Measures, Key Performance Indicators and Higher Performance Indicators using a structured process and introduces weighting factors to the indicators to reflect the difference in the perceived level of importance. The calculation methods of the assessment framework were verified, and finally, the framework was tested using hypothetical data.

Keywords Sustainability · Performance measures · Palm oil · Malaysia

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Introduction

The Malaysian palm oil industry has been developing rapidly over the past two decades due to increased demand for food, fuel and oleo-chemical products. At the same time, it has also changed the environmental landscape and resulted in other associated environmental impacts and social consequences. Whilst palm oil is sourced from renewable resources, it is not carbon neutral due to emissions from upstream conversion processes (Klaarenbeeksingel 2009).

The sustainability aspects of palm oil production have been the source of public concern (Rival and Levang 2014). Existing tools and methodologies for measuring sustainability of palm oil production, i.e. life cycle assessment, palm oil certification schemes, importing countries' trade standards, have weaknesses in terms of comprehensiveness (Lim et al. 2015), choice of indicators (Union of Concerned Scientists 2013) and objectives (Net Balance Foundation 2013; World Rainforest Movement 2010). Ecological footprint and environmental sustainability have specifically been considered in some recent studies (Musikavong and Gheewala 2017; Saswattecha et al. 2017). Whilst Baudoin et al. (2015) came up with a comprehensive sustainability assessment framework for palm oil industries, the scope of assessment is only limited to part of the supply chain, i.e. smallholder [farmers who own a small-scale, family-run farm that is less than 50 hectares (RSPO 2014)] production. A comprehensive framework involving multi-disciplinary research and multi-stakeholder involvement is thus required to measure the sustainability performance of developing strategies for sustainable palm oil production (Hansen et al. 2015; Lim et al. 2015).

Lim and Biswas (2015) have previously developed a comprehensive framework to assess social, economic and environmental sustainability of the entire supply chain of crude palm oil production in Malaysia. This framework applies

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multi-criteria hierarchical analysis using higher performance indicators (HPI), key performance indicators (KPI) and Performance Measures (PM) to assess the triple bottom line objectives. PMs are the smallest unit of these indicators measuring a particular sustainability criterion. All PMs are aggregated into KPIs, and then all KPIs are aggregated into HPIs. HPIs represent the main indicators of each sustainability objective. HPIs, KPIs and PMs were initially selected by reviewing palm oil sustainability standards, published government documents, national statistics and local industrial practices (Lim and Biswas 2015).

Whilst this framework could potentially overcome the weaknesses of existing assessment tools, it needs a scientific approach to select triple bottom line (TBL) indicators and to determine their weights (Lim and Biswas 2015). This paper presents the following improvements of the original framework.

- A structured methodology has been developed to select indicators (HPI, KPI, PM) as the applicability of the framework depends on the relevance and importance of these indicators.
- The use of average value of PMs has been avoided to determine KPIs. (For example, if the number of PMs for an environmental objective is more than that for an economic objective, then each environmental PM will have less impact than each economic PM on the overall performance of the corresponding sustainability objective.)
- Allocation of appropriate weights to PMs through stakeholder participation.
- The threshold values of some PMs have been determined through a rigorous review and consultation process as these values are deciding factors for sustainability outcomes.

Firstly, the paper describes the participatory approach considered for triple bottom line indicator development and then it discusses the detailed steps for developing these indicators. Finally, the paper discusses, and demonstrates, how the results of the revised framework can be utilised in the decision-making process for sustainable palm oil production.

Participatory approach for indicator development

A participatory approach that comprises both consensus survey and face-to-face interview was considered appropriate to engage stakeholders and area experts in the selection of PMs in order to improve the authenticity of the sustainability framework. Stakeholders who are directly and indirectly involved in the Malaysian crude palm oil supply chain have been given a platform through this survey to share their opinion and participate in the selection process of PMs. These stakeholders will ultimately be the users of this framework; thus, it is important to engage them at the early stages of the framework development to reduce any sort of conflict during implementation (Rosenström and Kyllönen 2007). Stakeholder engagement has been found to be an ideal means for developing sustainability indicators for social learning, management and ethical perspective (Mathur et al. 2008). Accordingly, a structured method has been designed for developing PMs as described below.

Description of steps for indicator development

Step 1: Questionnaire design and development

A questionnaire for consensus survey was designed to collect feedback and opinion from the stakeholders and area experts. The questionnaire was designed using a list of 22 TBL PMs from the previous work of Lim and Biswas (2015), which had been vetted through a thorough literature review process and provided an organised guideline and logical basis for the survey. The questionnaire collected opinions from the participants on (1) how relevant and (2) how important they think these baseline PMs are for assessing the sustainability of crude palm oil production. The questionnaire also had a provision for them to suggest additional PMs that may be more relevant for assessing the sustainability of crude palm oil production.

The questionnaire thus consisted of three sections:

Section I the participant had to assess the relevance of 22 PMs using a rating scale of 1–3 where 1 means ‘not relevant’, 2 means ‘relevant’ and 3 means ‘most relevant’.
Section II they had to evaluate the importance of each of 22 PMs on a scale of 1–4 where 1 is ‘least important’ and 4 is the ‘most important’.
Section III there was a provision for the participant to propose other relevant PMs, which were not listed in the questionnaire. They were also asked to rank the level of importance of these suggested PMs.

Step 2: Online survey development

Considering their diverse backgrounds the participants were contacted for their preference on the mode of survey (i.e. hard copy, face-to-face conversation or online survey). Local smallholders usually have limited access to Internet, and so online survey may not be convenient for them. In the case of academics and area experts, they are located at distant locations, but they have regular access to the Internet. The online survey was developed using Google Forms for participants who found it convenient to access the questionnaire through the Internet. About 60% of the government participants, 100% of academia, 90% of industry participants and 80% of NGO and local smallholders completed the survey online.

Step 3: Participant selection

It was important to identify the right participants in the PM selection process. In an 'expert consensus' survey participants or stakeholders should have a significant experience in the field, some influence on decision-making or have authority for judgement in the production process or have sound research track records in the area (Linstone and Turoff 1975). According to the Project Management Institute 'Stakeholder is an individual, group, or organization who may affect, be affected by or perceive itself to be affected by a decision, activity, or outcome of a project' (Project Management Institute 2013).

Likewise, the Roundtable of Sustainable Palm Oil (RSPO) developed its standard with inputs from stakeholders of 7 palm oil sectors, including oil palm producers, processors or traders, consumer goods manufacturers, retailers, banks/investors, and environmental and social non-governmental organisations (NGOs) (RSPO 2014). Study showed that the RSPO's stakeholder perceptions, in several aspects, were not in agreement with the local realities and sensibilities (Moreno-Peñaranda et al. 2015) mainly because of the dominance of one stakeholder group in the survey. Out of 7 stakeholders, 6 were from industry, who have vested interest in the development of the palm oil industry. This had also received public criticism as this dominancy had influenced the palm oil certification programme (Greenpeace 2013). These issues have been addressed in this research by incorporating an equal number of participants from each stakeholder group in order to conduct a more balanced survey.

Criteria for the selection of the right participants were developed through literature review (Darshini et al. 2013; Manik et al. 2013; Moreno-Peñaranda et al. 2015; Project Management Institute 2013) and brainstorming discussions using a mind map of stakeholders along the crude palm oil production supply chain. These criteria are as follows:

- Individual who is directly/indirectly involved with the production.
- Individual who is affected by the production.
- Individual who is the beneficiary of this production.
- Individual who incurs losses from the production.
- Individual who has authority to influence, control, terminate the production.
- Individual with subject matter expertise.

On the basis of these criteria, participants were grouped into 4 categories, being Government, Industry, Academia and Non-Government Organisations/Local Smallholders. These groups play four distinct roles and possess different perceptions on palm oil production, hence form a balanced participation and seek to obtain constructive, balanced survey outcomes. Similar classification was found in the study of Darshini et al. (2013) where palm oil stakeholders are classified into three groups, i.e. government agencies, industry players and non-governmental organisations. Shankar et al. (2016) had also classified stakeholders as ministries, regulatory agencies, the private sector, non-governmental organisations and academia to maintain a balanced participation. Table 1 shows the description of the four stakeholder groups who participated in the survey of this research.

Step 4: Data collection and analysis of survey responses

Subsequent to receiving ethics approval, potential participants (> 40 for each category) were contacted for acceptance to conduct the survey. Data were collected between September and December 2016 through online survey and face-to-face interview, depending on the participant's preference. A total of 40 participants with 10 from each of 4 stakeholder groups (25% of invited participants) agreed to participate in the survey on a voluntary basis. Participants were coded and categorised, but individual identity was kept confidential.

The survey data were then compiled to reflect the level of agreement on each PM (Table 2) and their level of importance (Table 3).

The conclusive messages that are drawn from Fig. 1 are as follows:

- All PMs received a high level of acceptance as confirmed by the affirmative responses received from more than 90% of the participants. Only $\leq$ 10% of the participants thought that 14 out of 22 PMs were irrelevant.
- The amount of water consumed by the plantation and production processes (i.e. Env. 8 in Fig. 1) was considered as relevant by only 40% of the participants. The low level of acceptance of this PM could be due to the fact that there is a high volume of rainfall in the tropical climate zone of Malaysia which adequately fulfils the water demand for irrigation of oil palm plantation (Muhammad-Muaz and Marlia 2014).
- Some participants from industry and the government regulator ($\approx$ 10%) commented that a few environment PMs (i.e. Env. 2 on NOx emission, Env. 3 on bio-oxygen demand of water discharge and Env. 9 on fossil fuel consumption) were irrelevant. This is because these parameters are already monitored under the DOE regulations (Environmental Quality Act 1974) and fossil fuel consumption is not significant in the palm oil production processes.

Table 1 Categories of participants

No.	Category	Type of participants	Background
1.	Government	Officers/regulator of the government of Malaysia	The policy maker Government officer who is involved in policy making, regulation enforcement and standard compliance related to palm oil production Hold positions as regional/state/head office officer
2.	Industry	Owners/managers/executives working along the crude palm oil supply chain	The development front who are operating the palm oil businesses Individual who is working in the palm oil industry (plantation and mill) Holding positions as executives and above, with a substantial amount of industry experience
3.	Academia	People who are researching and teaching on palm oil sustainability and relevant areas	The scientific knowledge base International and local academia/researchers who are working on palm oil sustainability
4.	Non-government organisations/local smallholders	Local community Smallholder International/local environmental and community based NGOs	People focused activity Representatives of the local community who are positively and negatively affected by the palm oil production Representatives of both local palm oil smallholders' associations, and NGOs working on environmental development, wildlife, wetland, forest conservation

As can be seen from Table 4, more than 60% of the participants had expressed agreement with the importance of these PMs. The PMs of economic objectives are more important (i.e. $\geq$ 80% of responses) than those for social and environmental objectives (60–90% of the responses). Some environmental and social PMs (i.e. local community involvement in decision-making, amount of water consumption and NOx emission) are perceived to be less important than other PMs. On the other hand, plantation yield, palm oil mill efficiency and the basic needs of palm oil workers, i.e. employment, clean water, health care, sanitation and housing which are considered as socio-economic PMs, have been found to be very important by most of the participants.

Step 5: Additional indicators from the participants

About 22 out of 40 participants proposed to include additional PMs including those on waste generation/waste handling and treatment, biodiversity, high conservation value forest (HCVF) and riparian mapping, conservation and protection at regional scale, plantation management performance measures, management commitment, environmental impact assessment, cost–benefit analysis, water pollution, machinery efficiency, smallholder/local community inclusion in economic development, distribution of wealth, fair partnership, occupational safety and health of workers, transparency, awareness and communication, life cycle thinking and corporate stewardship social responsibility (CSR).

Most of the PMs suggested were not considered as they overlapped with the existing PMs/KPIs/HPIs, some were beyond the scope of the assessment framework, some were more on regulatory aspects, some considered neoclassical economics points of view (i.e. cost–benefit analysis), and some are strategies rather than indicators. A detailed analysis on respondents' feedback and opinion is summarised in Table 5. The texts in italic in Table 5 are the responses made by the authors/researcher.

Step 6: Final selection of indicators and their weightings

The following criteria have been used to finalise the list of PMs.

- The PMs were *voted* as 'relevant' AND 'important' by more than 50% of the participants.
- The PMs that were *proposed* by more than 5 of the 22 participants (> 25%).

On the basis of these criterions, one existing PM (i.e. amount of water consumed by the plantation and production processes) has been removed from the framework as less than 40% of the participants rated it as relevant. 'Species loss' has been included as a new PM for measuring the Biodiversity KPI.

From the feedback, some PMs had to be transferred from social to economy sustainability objective (i.e. employment opportunity for the local people and the percentage of smallholder equity). In addition the criteria for ranking value of PM 'plantation practice' and 'local community involvement

Table 2 Data summary for level of relevance of PMs

Performance measure	Relevance				Total
		1	2	3	
	No response	Not relevant	Less relevant	Relevant	
1. Greenhouse gas emission throughout the crude palm oil production	0	1	9	30	40
2. NOx emission	0	4	14	22	40
3. Biological oxygen demand of water discharged	0	3	8	29	40
4. Nitrate-nitrogen level in waterway nearby the plantation/mill	0	2	10	28	40
5. % of biomass (i.e. residue or waste) recovered/recycled throughout the production process for future use	0	0	10	30	40
6. Plantation practice—how the oil palm trees are planted (e.g. by replacing forest, large area replanting, patch/strips planting or crops rotation)	0	0	12	28	40
7. Type of land used for plantation (e.g. peat land/high conservation value forest/secondary forest/existing agricultural land)	0	0	14	26	40
8. Amount of water consumed by the plantation and production processes	0	0	24	16	40
9. Fossil fuel (e.g. diesel, gas) consumed per tonne of oil produced	0	3	13	24	40
10. Plantation yield (i.e. amount of Fresh Fruit Bunches produced per hectare)	0	0	6	34	40
11. Palm oil mill production efficiency (i.e. amount of crude palm oil produced per tonne of fresh fruit bunches)	0	0	8	32	40
12. Actual business growth rate versus sustainable growth rate of the palm oil company (is the business financial situation healthy?)	1	2	12	25	40
13. Average annual income per worker	1	3	5	31	40
14. Employment opportunity for the local people	1	1	8	30	40
15. Workers' accessibility to clean water supply for drinking and daily use	1	3	7	29	40
16. Workers' accessibility to healthcare services	1	3	10	26	40
17. Provision of sanitation facilities to workers	1	3	9	27	40
18. Provision of housing facilities to workers	1	3	10	26	40
19. Smallholders' equity— % of palm oil sourced from smallholders	0	2	14	24	40
20. Local communities' ability to access information and knowledge about the plantation and mill	1	0	18	21	40
21. Local community (i.e. smallholders, neighbours, workers of plantation and mill) involvement in decision-making that involves them	0	1	16	23	40
22. Level of community acceptance to plantation and mill activities	0	1	10	29	40

Numbers in cells represent the number of respondents. Sum of all numbers for each PM is 40, which is the total number of respondents

in decision-making' had to be redefined, as the participants commented that the current definition of plantation practice and local community involvement in decision-making is very limited.

The list of PMs in Lim and Biswas' framework (Lim and Biswas 2015) was thus revised after considering feedback from stakeholders and area experts (Table 6).

Once the PMs were finalised, the following two tasks were performed:

(1) Weight was allocated to each PM based on the responses of the 40 participants.
(2) Ranking values for the new/revised PMs were ascertained.
(1) *Application of weights* The calculation of weights for PMs was based on the work of Manik et al. (2013). The responses in terms of the level of importance of PMs provided by 40 participants, as shown in Table 3, have been used to calculate the weights of PMs.

The weight of each PM was calculated using Eq. 1.

$$W_j = n_{j1} \times 1 + n_{j2} \times 2 + n_{j3} \times 3 + n_{j4} \times 4 + n_{j5} \times 5 \tag{1}$$

where $j = 1, 2, 3, \ldots\ldots\ldots\ldots M$, is the performance measure (PM)

n_{j1} = number of 'no responses' for PM of j,

n_{j2} = number of 'least important' responses for PM of j,

n_{j3} = number of 'less important' responses for PM of j,

n_{j4} = number of 'important' responses for PM of j,

n_{j5} = number of 'most important' responses for PM of j,

Table 3 Data summary for level of importance for PMs

Performance measure	Level of importance					Total
		1	2	3	4	
	No response	Least important	Less important	Important	Most important	
1. Greenhouse gas emission throughout the crude palm oil production	1	1	4	18	16	40
2. NOx emission	1	5	10	15	9	40
3. Biological oxygen demand of water discharged	1	2	6	12	19	40
4. Nitrate-nitrogen level in waterway nearby the plantation/mill	1	1	6	16	16	40
5. % of biomass (i.e. residue or waste) recovered/recycled throughout the production process for future use	1	0	6	17	16	40
6. Plantation practice—how the oil palm trees are planted (e.g. by replacing forest, large area replanting, patch/strips planting or crops rotation)	1	0	4	16	19	40
7. Type of land used for plantation (e.g. peat land/high conservation value forest/secondary forest/existing agricultural land)	1	1	6	15	17	40
8. Amount of water consumed by the plantation and production processes	1	3	11	15	10	40
9. Fossil fuel (e.g. diesel, gas) consumed per tonne of oil produced	1	4	7	16	12	40
10. Plantation yield (i.e. amount of fresh fruit bunches produced per hectare)	1	1	4	8	26	40
11. Palm oil mill production efficiency (i.e. amount of crude palm oil produced per tonne of fresh fruit bunches)	1	0	4	8	27	40
12. Actual business growth rate versus sustainable growth rate of the palm oil company (is the business financial situation healthy?)	2	1	5	13	19	40
13. Average annual income per worker	1	1	5	15	18	40
14. Employment opportunity for the local people	0	1	4	14	21	40
15. Workers' accessibility to clean water supply for drinking and daily use	0	2	3	13	22	40
16. Workers' accessibility to healthcare services	0	1	5	10	24	40
17. Provision of sanitation facilities to workers	0	1	3	15	21	40
18. Provision of housing facilities to workers	0	2	3	17	18	40
19. Smallholders' equity— % of palm oil sourced from smallholders	1	2	8	11	18	40
20. Local communities' ability to access information and knowledge about the plantation and mill	2	1	7	17	13	40
21. Local community (i.e. smallholders, neighbours, workers of plantation and mill) involvement in decision-making that involves them	1	1	11	10	17	40
22. Level of community acceptance to plantation and mill activities	1	0	8	15	16	40

Numbers in cells represent the number of respondents. Sum of all numbers for each PM is 40, which is the total number of respondents

Total weight for M number of PMs has been calculated as follows:

$$W_{\text{Total}} = \sum_{j=1}^{M} W_j \tag{2}$$

The normalised weight (W'_j) for each PM has been calculated as follows:

$$W'_j = \frac{W_j}{W_{\text{Total}}} \tag{3}$$

Table 7 shows that the normalised weights of 22 PMs are aggregated into 11 KPIs and then these 11 KPIs are aggregated into 5 HPIs.

(2) *Ranking value criteria for PMs* The ranking value criteria for each PM were slightly modified from the study of Lim and Biswas (2015), as the threshold value or expectation in the current analysis is now considered as the maximum score on the scale. Instead of ranking the PM performance from 1 to 5 with level 3 as the threshold value, the current approach would rank the PM performance from 1 to 5 with level 5 as the threshold or expected performance value. With this approach, threshold value defines the targeted sustainability performance, and the assessment framework would measure how close the existing situation of palm oil production is to achieving sustainability threshold values.

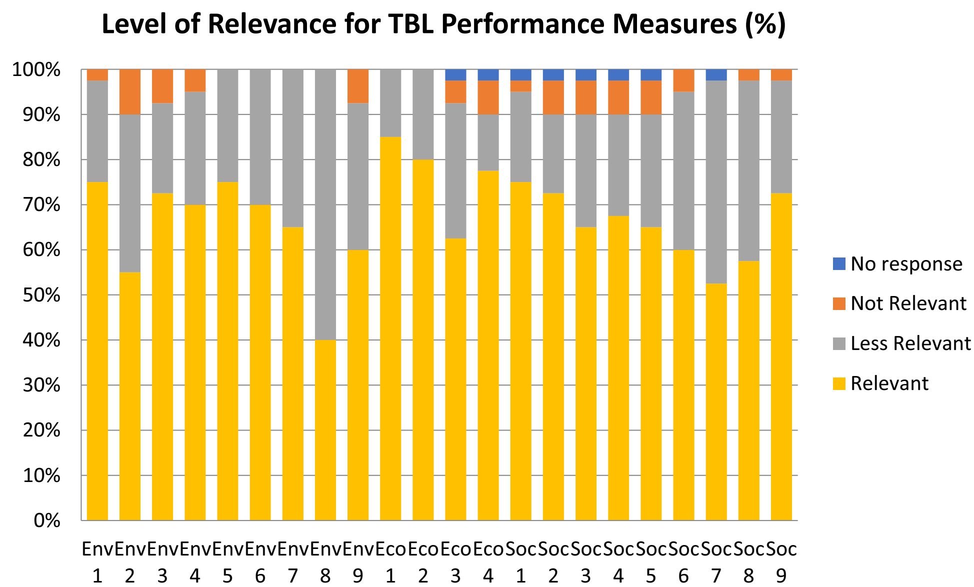

Fig. 1 Level of relevance for TBL performance measures in % (Env = environmental; Eco = economic; Soc = social)

Table 4 Importance ranking of 22 PMs

% of participant who rated it as important/most important	Ranking	PM code	Description
≥ 90%	1	Soc 4	Provision of sanitation facilities for workers
≥ 80%	2	Env 6	Plantation practice—how are oil palm trees planted? (e.g. by replacing forest, large area replanting, patch/strips planting or crops rotation)
	2	Eco 2	Palm oil mill production efficiency (i.e. amount of crude palm oil produced per tonne of fresh fruit bunches)
	2	Soc 1	Employment opportunity for the local people
	2	Soc 2	Workers' accessibility to clean water supply for drinking and daily use
	2	Soc 5	Provision of housing facilities to workers
	7	Env 1	Greenhouse gas emissions throughout the crude palm oil production
	7	Eco 1	Plantation yield (i.e. amount of fresh fruit bunches produced per hectare)
	7	Soc 3	Workers' accessibility to healthcare services
	8	Env 5	% of biomass (i.e. residue or waste) recovered/recycled throughout the production process for future use
	8	Eco 4	Average annual income per worker
	9	Env 4	Nitrate-nitrogen level in waterway near plantation sites/mills
	9	Env 7	Type of land used for plantation (e.g. peat land/high conservation value forest/secondary forest/existing agricultural land)
	9	Eco 3	Actual business growth rate versus sustainable growth rate of the palm oil company (is the business financial situation healthy?)
≥ 70%	10	Env 3	Biological oxygen demand of industrial effluents
	10	Soc 9	Level of community acceptance to plantation and mill activities
	11	Soc 7	Local communities' ability to access to information and knowledge about the plantation and oil mills
	12	Soc 6	Smallholders' equity— % of palm oil sourced from smallholders
	13	Env 9	Fossil fuel (e.g. diesel, gas) consumed per tonne of oil produced
≥ 60%	14	Soc 8	Local community (i.e. smallholders, neighbours, workers of plantation and mill) involvement in the decision-making process
	15	Env 8	Water consumption by the plantation and production processes
	16	Env 2	NOx emissions

Table 5 Other performance measures proposed and additional comments

No.	TBL element	Performance measures proposed/comments
1.	Env.	*Waste generation/waste handling and treatment* Three participants had suggested to consider the conversion of large amount of biomass waste from crude palm oil supply chain to organic fertiliser to improve soil fertility and protect the environment as a viable solution. These participants came from a variety of backgrounds i.e. government, academia and industry One of the PMs captured this issue as it involves biomass waste handling i.e. Env. 5% of biomass (i.e. residue or waste) recovered/recycled throughout the production process for future use
2.	Env.	*Biodiversity* Six participants from all 4 respondent categories emphasised the importance of biodiversity as 'density of biodiversity of flora and fauna that tells us the effectiveness of ecosystem services', and also the loss of species and wildlife is a common concern of palm oil production'. It was further suggested that biodiversity conservation programme/management practices should be applied, and the 'overall impact on biodiversity' as well as the 'effectiveness of conservation efforts' should be measured Biodiversity is a KPI in the Lim and Biswas's Framework. This KPI was measured using two PMs i.e. Land Use and Plantation Practice as these two PMs have direct impact on biodiversity conservation. From the feedback, probably a more direct measure of biodiversity e.g. species loss is desired and should be considered
3.	Env.	*High conservation value forest (HCVF) and riparian mapping, conservation and protection at regional scale* Five participants from 2 categories i.e. academia and smallholder/NGO expressed their concerns on the performance measure for HCVF and wetlands. According to them, HCVF and wetland protection should implicitly be included in land use change and forest protection. In addition they have also suggested the inclusion of land mapping, planning at regional scale for optimisation and productive land use purposes. They also suggested to include efforts and means that were put into the protection of HCVF e.g. forest replanting. It was also mentioned that 'productive use and stewardship of land, along with conservation of natural vegetation, is the basis for sustainability' The sustainability assessment framework is intended to be applied by the supply chain, which has no control and influence over the macro level land planning in the Malaysian context. The land planning is under the jurisdiction of the States Government. The supply chain, however, could decide which type of 'agricultural land', approved by the Land and Survey Department Malaysia, to be acquired and used as site for oil palm plantation. This is measured in PM of Env. 7: Type of land used for plantation (e.g. peat land/high conservation value forest/secondary forest/existing agricultural land). On the other hand, land mapping and plantation planning within the control of the supply chain is measured under PM of Env. 6: Plantation Practice—how the oil palm trees are planted (e.g. by replacing forest, large area replanting, patch/strips planting or crops rotation)
4.	Env.	*Plantation management performance measures* Six participants from academic institutions, regulatory authorities and smallholder/NGO provided a wide range of suggestions related to plantation practice and management as performance measure. These plantation practices/management tools include the use of certified planting material e.g. seedling as the first step to yield assurance, use of organic fertiliser for soil structure improvement, integrated pest management to reduce chemical consumption (herbicide and pesticide), zero-burning principle during replanting to prevent air pollution and GHG emissions, and transparent mapping of plantation boundaries including vegetation and soil type and declivity as a 'key to certification, community mapping and bushfire prevention' The participants highlighted that the plantation management practices 'maintain or improve the condition of the soil and water', and it 'affects not only the yield but also the level of carbon sequestration and GHG emissions' PM of Env. 6: Plantation Practice have been revised to capture requirements for good plantation management
5.	Env.	*Management commitment* Two participants from the industry and local smallholder/NGO categories shared the view that the management of palm oil companies should demonstrate their commitment to environmental preservation by setting improvement targets, drafting action plans, and allocating sufficient resources and budget to address the issue The sustainability assessment intends to measure sustainability performance of palm oil production based on TBL objectives. The assessment measures the 'results' of the sustainability level, rather than checking if there are means to achieve the outcomes. Management commitment is not a sustainability objective, but it is a means to achieve the intended sustainability performance
6.	Env.	*Environmental impact assessment* One participant from the industry category suggested the Environmental Impact Assessment (EIA) be included as one of the PMs EIA is already a regulatory requirement for new projects under the Malaysia Environmental Quality Act. This happens before the commencement of the project
7.	Eco.	*Cost–benefit analysis* One participant from the Local/NGO category suggested to conduct cost–benefit analysis to measure if the environment exploitation and consumption of natural resources for the sake of palm oil production is justified This sustainability assessment framework measures sustainability objective independently to check the performance of each TBL element. Cost–benefit analysis suggests a compromise of environment integrity and social equity for economic return, which is not relevant to this framework

Table 5 (continued)

No.	TBL element	Performance measures proposed/comments
8.	Env.	*Water pollution* One participant from the local smallholders/NGO category highlighted the importance of controlling pollution of the river as many indigenous people in Malaysia still depend on river water for their daily use Water pollution is measured through PM Env. 3: Bio-oxygen demand of water discharge, which is the most important parameter for water pollution, applied by the Department of Environment, Malaysia
9.	Env.	*Machinery efficiency* One participant from the industry category proposed to include machinery efficiency as one of the performance measures as it is important to lower fuel consumption and emission Machinery efficiency is indirectly measured through PM of Env. 9: Fossil fuel consumption per tonne of oil produced
10.	Env., eco and soc	*Relative performance concept* Three participants from the industry and government categories shared the view that sustainability performance of palm oil (land use, yield, pollution, footprints, job creation, etc.) should be judged in comparison with sustainability performance of other oil crops. These participants had the opinion that relative sustainability performance is important for selecting a better option to meet the food and fuel demand, and to be fair to developing country like Malaysia 'Best available option' could be a guideline in setting threshold of ranking value for PMs. A similar approach is applied in the Lim and Biswas (2015) framework
11.	Env., eco and soc	*Life cycle consideration and minimum performance expected* Five participants from academic and local smallholder/NGO categories suggested to consider life cycle thinking in measuring the PMs of this assessment. These participants showed concern about the boundary of the assessment (to include the supply chain from cradle-to-grave, by-products). The participants also mentioned that statutory limits should be the minimal requirement of the performance, and the supply chain shall 'migrate from legal compliance to a more active role of protection and prevention' Life cycle assessment shall be used to calculate GHG emission measure and the suggestion to set the suitable boundary should be considered. Statutory requirement could be considered as a threshold of ranking values for PMs. A similar approach has already been considered in Lim and Biswas (2015) framework
12.	Eco.	*Smallholder/local community inclusion in economic development, distribution of wealth* Six participants from industry, academic, local smallholders and NGO categories emphasised that the local community should benefit from the palm oil development through 'food and job' security, local involvement in the palm oil business, and the return of palm oil earnings to enhance local development. It was also suggested that measures on 'appointment of local people at managerial level in the supply chain', 'fraction of earning going to local staff salary' be considered. Rather than economic benefits at national or global level, the participants viewed sustainable economy as long-term growth and income stability of the local community, in exchange for their land and natural environment Job creation for the local people was already considered in PM of Soc. 1: Employment opportunity for the local people and return of palm oil production to the local people was considered in PM of Eco. 4: Average annual income per worker and PM of Soc. 6: Smallholder equity— % of palm oil source from local smallholders. These PMs should all be considered under the economic sustainability objective instead of social sustainability objective
13.	Eco.	*Fair partnership* Three participants from the academic, local smallholder and NGO categories suggested that PMs reflecting fair partnership between the palm oil company and the local people be included in the assessment. It was suggested that the principle of 'Free prior and informed consent' (FPIC) or agreement on land tenure' should be applied to prevent land disputes and exploitation of the local people The existing PMs Soc. 7, 8 and 9 have already captured this aspect, as they measure the local community engagement through sharing information, involvement in decision-making and receiving acceptance of the local people. FPIC/legally binding land agreement could be included as factor to measure these PMs
14.	Soc.	*Occupational safety and health of workers* Two participants, from academic and industry backgrounds, suggested that occupational safety and health performance should be a part of the social performance measure. There was a great concern about the safety of workers working in a high pressure and high temperature environment in the mill, and about impact to their health due to long periods of exposure to dangerous chemical i.e. pesticides and herbicides Feeling safe and free from danger at work could be a new perspective to basic human needs other than job security, shelter, access to clean water, medical treatment, hygienic sanitary system
15.	Soc.	*Transparency, awareness and communication* Two participants, one each from government and local smallholder/NGO category requested transparency in sharing the information of palm oil supply chain activities with the local people and regulator. This is important for awareness of the potential impact on the local people, and check and balance for the regulator Sharing of information is already included in PM of Soc. 7: Local communities' ability to access information and knowledge about the plantation and mill. The PM should be rephrased to suggest a proactive action i.e. sharing information and knowledge about the plantation and mill activities with the regulator and local people

Table 5 (continued)

No.	TBL element	Performance measures proposed/comments
16.	Soc. eco.	*Corporate stewardship social responsibility (CSR)* One participant from industry proposed to incorporate CSR as one of the PMs as it indicates the development and progression of the local community. Two participants from local smallholder/NGO groups proposed include training, guidance and support provided to stakeholders in the supply chain in oil palm plantation and environment protection, which is relevant to CSR This is beyond the capacity of oil palm producers to achieve socio-economic development through CSR, as their main task is to run the oil palm businesses with less environmental impacts and social consequences. It would have been ideal if corporations in the palm oil supply chain could steward the social economic development of the local community through their CSR programmes, and bring positive change to the community along with their business activities

The texts in italic are the responses made by the authors/researcher

Table 6 Revised sustainability assessment framework

Sustainability objectives		Headline performance indicator (HPI)		Key performance indicator (KPI)		Performance measures (PM)
Environment	1	Natural capital conservation	1.1	Climate change	1.1.1	GHG emission
			1.2	Air, water and soil quality	1.2.1	NOx emission intensity from palm oil mill
					1.2.2	Biological oxygen demand of water discharged from POME pond
					1.2.3	Soil nitrate level measured through pH in waterway
			1.3	Waste generation	1.3.2	% biomass recovery/recycling
			1.4	Biodiversity	1.4.1	Plantation practice
					1.4.2	Land use
					1.4.3	Species loss
			1.5	Resources consumption	1.5.1	Fossil fuel consumption intensity (output/input energy ratio)
Economy	2	Business continuity and resiliency	2.1	Productivity efficiency	2.1.1	Plantation yield
					2.1.2	Mill production efficiency
			2.2	Consistent profitability	2.2.1	Actual growth rate
	3	Sharing of economic power	3.1	Relative poverty	3.1.1	Average annual income per worker
			3.2	Local community inclusion and distribution of wealth	3.2.1	Employment opportunity for the locals
					3.2.2	Smallholders' equity
Social	4	Social wellbeing	4.1	Meeting essential human needs	4.1.1	Workers' accessibility to water supply
					4.1.2	Workers' accessibility to health care
					4.1.3	Provision of sanitation facilities to workers
					4.1.4	Provision of housing facilities to workers
	5	Social equity	5.1	Local community empowerment and engagement	5.1.1	Access to information and knowledge
					5.1.2	Fair Partnership and Community Involvement in Decision Making.
					5.1.3	Level of community acceptance of plantation and mill activities

Table 7 Weight distribution for PM, KPI, HPI and sustainability objectives

	PM	Overall weight		KPI	Overall weight		HPI	Overall weight	Sust. obj.	Overall weight
1.1.1	GHG emission	0.0450	1.1	Climate change	0.0450	1	Natural capital conservation	0.4046	Env.	0.4046
1.2.1	NOx emission intensity from palm oil mill	0.0393	1.2	Air, water and soil quality	0.1284					
1.2.2	Biological oxygen demand of water discharged from POME pond	0.0447								
1.2.3	Soil nitrate level measured through pH in waterway	0.0444								
1.3.2	% biomass recovery/recycling	0.0450	1.3	Waste generation	0.0450					
1.4.1	Plantation practice	0.0463	1.4	Biodiversity	0.1448					
1.4.2	Land use	0.0447								
1.4.3	Species loss	0.0538								
1.5.1	Fossil fuel consumption intensity (output/input energy ratio)	0.0415	1.5	Resources consumption	0.0415					
2.1.1	Plantation yield	0.0476	2.1	Productivity efficiency	0.0961	2	Business continuity and resiliency	0.1408	Eco.	0.2770
2.1.2	Mill production efficiency	0.0485								
2.2.1	Actual growth rate	0.0447	2.2	Consistent profitability	0.0447					
3.1.1	Average annual income per worker	0.0452	3.1	Relative poverty	0.0452	3	Sharing of economic power	0.1362		
3.2.1	Employment opportunity for the local	0.0471	3.2	Local community inclusion and distribution of wealth	0.0910					
3.2.2	Smallholders' equity	0.0439								
4.1.1	Workers' accessibility to water supply	0.0471	4.1	Meeting essential human needs	0.1882	4	Social wellbeing	0.1882	Soc.	0.3184
4.1.2	Workers' accessibility to health care	0.0476								
4.1.3	Provision of sanitation facilities to workers	0.0474								
4.1.4	Provision of housing facilities to workers	0.0460								
5.1.1	Access to information and knowledge	0.0425	5.1	Local community empowerment and engagement	0.1303	5	Social equity	0.1303		
5.1.2	Community involvement in decision making	0.0433								
5.1.3	Level of community acceptance of plantation and mill activities	0.0444								
	Sum	1.0000			1.0000			1.0000		1.0000

The ranking values of criterion for existing PMs were adopted from Lim and Biswas (2015), and a ranking value has been developed for the new PM ‘species loss’.

Since measuring species loss is a time-consuming task and requires additional investment in thorough experimental research (Encyclopedia of biodiversity/edited by Simon Levin 2013) (Chiarucci et al. 2011), the local community has to be interviewed on the basis of their observation on species loss during the palm oil plantation period in their region. A similar participatory approach has been applied by other researchers (Beaudreau and Levin 2014; Bednar-Friedl et al. 2009; Webber and Hill 2014). In some studies (Beaudreau and Levin 2014) the local ecological knowledge was proven to be in agreement with scientific data.

The criterion of the ranking value for PM 1.4.3 Species Loss has been proposed as follows:

1. Majority of the locals agree that there is a serious species loss due to palm oil development and no conservation effort has been made at all.
2. Majority of the locals agree that there is a significant species loss due to palm oil development with little conservation effort being made.
3. Majority of the locals agree that there are some species loss due to palm oil development with little conservation efforts being made.
4. Majority of the locals agree that there are some species loss due to palm oil development although significant conservation efforts have been made.
5. Majority of the locals agree that there is no species loss due to palm oil development and proactive programmes for conservation were conducted.

Threshold/expectation value is set at ‘no species loss’ due to palm oil development. This will take into account the species loss throughout the food chain as the extinction of one species affects other species in the chain.

Using the participants’ feedback, the criteria for PM 1.4.1 Plantation Practice in Lim and Biswas (2015) under the KPI 1.4 of Biodiversity have been revised as follows:

1. Replacement of forest.
2. Total/large area replanting.
3. Increase heterogeneity through patch planting.
4. Increase connectivity through successive strips/connectivity.
5. Reduce severity of disturbance through variable rotation.

The previous ranking value criteria of PM 1.4.1 Plantation Practice only considered the influence of landscape heterogeneity on the loss of biodiversity, and thus, it has been revised as follows:

- Use of certified seedling.
- Application of zero-burning principle throughout the planting/replanting process.
- Clear plantation boundaries/landscape mapping.
- Increase of landscape heterogeneity through patch planting/successive strips and connectivity/variable rotation instead of large area planting (Azhar et al. 2015; Luskin and Potts 2011).
- Use of organic fertiliser.
- Strategies to reduce the use of chemicals (e.g. integrated pest management or integrated livestock farming).

The criteria for ranking value of PM 1.4.1 have thus been revised as follows:

1. Meet < 3 of the plantation practice requirements.
2. Meet 3/6 plantation practice requirement.
3. Meet 4/6 plantation practice requirements.
4. Meet 5/6 plantation practice requirements.
5. Meet all the plantation practice requirements.

Following the feedback received from the consensus survey, the criteria of PM of 5.12 (which is Fair Partnership and Community Involvement in Decision Making) now ensure the free, prior and informed consent (FPIC) between the plantation company and the local community, particularly on the issue of land use. Thus, the criterion of ranking value of this PM has been revised as follows:

1. No involvement at all in decision-making/no prior consultation of land use.
2. Indirect communication channels are available/no prior consent for land use.
3. Local community could provide feedback to plantation owner/mill management through established channels on any issues that would affect them, and there is free, prior and informed consent (FPIC) regarding the use of land.
4. Local community has representation in plantation/mill HSE committee, and FPIC exists for the local people.
5. FPIC is treated as mandatory in any activities; legally binding land agreement is available.

The final PMs and their ranking value criteria have been listed in Table 8.

Step 7: Testing of developed framework and indicators using hypothetical data

Ranks of existing PMs were determined using hypothetical data from Lim and Biswas (2015). In the case of the new PM for species loss, it was ranked 1, as the majority of the locals agree that there is a serious species loss due to palm

Table 8 Reviewed performance measures and the ranking value criteria

Performance measures	Ranking value	
1.1.1 GHG emission	1	> 1 tCO2 eq/tonne CPO
	2	> 0.8 tCO2 eq/tonne CPO
	3	0.5–0.8 tCO2 eq/tonne CPO
	4	< 0.50 tCO2 eq/tonne CPO
	5	< 0.15 tCO2 eq/tonne CPO
1.2.1 NOx emission intensity from palm oil mill	1	> 500 mg/m3 emission (continuous)
	2	> 450 mg/m3 emission (continuous)
	3	> 400 mg/m3 emission (continuous)
	4	> 350 mg/m3 emission (continuous)
	5	< 350 mg/m3 emission (continuous)
1.2.2 Biological oxygen demand of water discharged from POME pond	1	> 250 mg/l (3 days, 30 °C)
	2	> 200 mg/l (3 days, 30 °C)
	3	> 150 mg/l (3 days, 30 °C)
	4	> 100 mg/l (3 days, 30 °C)
	5	< 100 mg/l (3 days, 30 °C)
1.2.3 Soil nitrate level measured through pH in waterway	1	Total nitrogen > 400 mg/l
	2	Total nitrogen > 350 mg/l
	3	Total nitrogen > 300 mg/l
	4	Total nitrogen > 250 mg/l
	5	Total nitrogen < 200 mg/l
1.3.1 % biomass recovery/recycling	1	< 25% recovery
	2	> 25% recovery
	3	> 50% recovery
	4	> 75% recovery
	5	100% recovery
1.4.1 Plantation practice	1	Meet < 3 of the plantation practice requirements
	2	Meet 3/6 plantation practice requirement
	3	Meet 4/6 plantation practice requirements
	4	Meet 5/6 plantation practice requirements
	5	Meet all the plantation practice requirements
1.4.2 Land use	1	Planted on Peat Land/HCVF
	2	Planted on secondary forest/replaced other crops
	3	Replanting on agricultural land
	4	Replanting with Best Management Practice
	5	Replanting with agricultural intensification
1.4.3 Species loss	1	Majority of the locals agree that there is a serious species loss due to palm oil development and there is no conservation effort at all
	2	Majority of the locals agree that there is a significant species loss due to palm oil development and there are little conservation efforts seen
	3	Majority of the locals agree that there are some species loss due to palm oil development and there are little conservation efforts seen
	4	Majority of the locals agree that there are some species loss due to palm oil development although significant conservation efforts are put in
	5	Majority of the locals agree that there is no species loss due to palm oil development and there are proactive programmes for conservation

Table 8 (continued)

Performance measures	Ranking value
1.5.2 Fossil fuel consumption intensity (output/input energy ratio)	1 < 6
	2 < 7
	3 < 8
	4 < 9
	5 ≥ 9
2.1.1 Plantation yield	1 < 16 tonne per ha per year
	2 < 17 tonne per ha per year
	3 < 18 tonne per ha per year
	4 < 19 tonne per ha per year
	5 ≥ 19 tonne per ha per year
2.1.2 Mill production efficiency	1 < 0.18 tonne CPO per tonne FFB
	2 < 0.19 tonne CPO per tonne FFB
	3 < 0.20 tonne CPO per tonne FFB
	4 < 0.21 tonne CPO per tonne FFB
	5 ≥ 0.21 tonne CPO per tonne FFB
2.2.1 Actual growth rate	1 > 15% deviation from sustainable growth rate
	2 15% deviation from sustainable growth rate
	3 10% deviation from sustainable growth rate
	4 5% deviation from sustainable growth rate
	5 0% deviation from sustainable growth rate
3.1.1 Average annual income per worker	1 < 20% of national median income
	2 < 30% of national median income
	3 < 40% of national median income
	4 < 50% of national median income
	5 ≥ 50% of national median income
3.2.1 Employment opportunity for the local	1 < 25% local employment
	2 ≥ 25% local employment
	3 > 50% local employment
	4 > 75% local employment
	5 100% local employment
3.2.2 Smallholders' equity	1 <10% of CPO sourced from smallholders
	2 < 20% of CPO sourced from smallholders
	3 < 30% of CPO sourced from smallholders
	4 < 50% of CPO sourced from smallholders
	5 ≥ 50% of CPO sourced from smallholders
4.1.1 Workers' accessibility to water supply	1 < 25% accessible to portable water
	2 > 25% accessible to portable water
	3 > 50% accessible to portable water
	4 > 75% accessible to portable water
	5 100% accessible to portable water
4.1.2 Workers' accessibility to health care	1 < 25% accessible to healthcare facilities
	2 > 25% accessible to healthcare facilities
	3 > 50% accessible to healthcare facilities
	4 > 75% accessible to healthcare facilities
	5 100% accessible to healthcare facilities
4.1.3 Provision of sanitation facilities to workers	1 < 25% accessible to sanitation facilities
	2 > 25% accessible to sanitation facilities
	3 > 50% accessible to sanitation facilities
	4 > 75% accessible to sanitation facilities
	5 100% accessible to sanitation facilities

Table 8 (continued)

Performance measures	Ranking value
4.1.4 Provision of housing facilities to workers	1 < 25% provision to housing facilities
	2 > 25% provision to housing facilities
	3 > 50% provision to housing facilities
	4 > 75% provision to housing facilities
	5 100% provision to housing facilities
5.1.1 Sharing of information with the local community	1 No information available
	2 Information available but local community are not informed
	3 Local community informed prior to the plantation and mill development
	4 Local community informed periodically on the plantation and mill development
	5 Local community are timely updated
5.1.2 Fair Partnership and Community Involvement in Decision Making	1 No involvement at all in decision-making/No prior consultation of land use
	2 Indirect communication channels are available/No prior consent of land use
	3 Local community could provide feedback to plantation owner/mill management through establish channel on any issues affecting them, and there is free, prior and informed consent (FPIC) in using the land
	4 Local community has representation in plantation/mill HSE committee, FPIC is available with considerations offered to the local people
	5 FPIC is treated as mandatory in any activities, legally binding land agreement is available
5.1.3 Level of community acceptance of plantation and mill activities	1 < 20% agreement from community
	2 < 30% agreement from community
	3 < 40% agreement from community
	4 < 50% agreement from community
	5 > 50% agreement from community

oil development with no conservation effort being made by the plantation companies. According to WWF, the number of mammal species reduced from 30 of 80 to around 11 due to conversion of primary forest or virgin forest to oil palm plantations (Clay 2004; WWF 2017a). Another newly revised PM for plantation practice was ranked 2 as there is a potential to meet half of the plantation practice requirements (i.e. firstly, certification of seeding is controlled by the Malaysian Palm Oil Board (MPOB). Secondly, there is a clear plantation boundaries/landscape map provided by the Land and Survey Department as part of the legal process. Lastly, the consumption of herbicide and pesticide has been reduced due to government initiatives (e.g. integrated pest management or integrated livestock farming since 1980/1990s) [Sime Darby Plantation Official Website 2017; WWF 2017b].

The revised PM for Fair Partnership and Community Involvement in Decision Making was ranked 2 as the local people only have an indirect communication channel with the oil palm plantation and mill company through community leaders. Also, there still exists a land use dispute between the oil palm plantation and the local natives (Colchester 2011; Custodio 2017; Dayang Norwana et al. 2011; Pearce 2017), which means that the FPIC for land use is not fully practised.

Weights and ranks of PMs, which were discussed in the previous section, have been used to calculate the KPI score using Eq. 4 (Lim and Biswas 2015):

$$\mathrm{KPI} = \frac{\sum_{j}^{P} W_j' R_j}{\sum_{j}^{P} W_j'} \tag{4}$$

where $R_j = R_1, R_2, \ldots R_M$, ranks of PMs

P = total number of PMs per KPI

Performance of each HPI is calculated as average performance of related KPIs (Lim and Biswas 2015).

$$\mathrm{HPI} = \frac{\sum_{k}^{K} \mathrm{KPI}_k}{K} \tag{5}$$

where $KPI_k = KPI_1, KPI_2 \ldots KPI_K$ represent scores of KPIs

And, overall sustainability performance is calculated as the average ranking of HPIs related to triple bottom line objectives (Lim and Biswas 2015).

$$\text{Overall sustainability performance} = \frac{\sum HPI_1 + HPI_2 + \cdots + HPI_N}{N} \tag{6}$$

where $HPI_1, HPI_2, \ldots HPI_n$ represents score for first HPI, second HPI and nth HPI of respective sustainability objective.

The overall sustainability assessment result is presented in Table 9, and the distribution of PM, KPI, HPI and TBL sustainability objective scores is presented in Fig. 2.

Results of sustainability assessment and gap analysis

The overall score of sustainability was 3.14 out of 5, which was well below the new threshold value or the highest level of expectation of 5.

Figure 2 shows that the scores for all triple bottom line objectives were not that different from each other, as the scores for economic, environmental and social objective are 3.12/5, 3.13/5 and 3.17/5, respectively. These scores confirm that these TBL objectives perform below the threshold value or expectation and, therefore, there is a need to improve some PMs of these sustainability objectives. The PMs which are responsible for lowering the overall score of the HPI are known as 'hot spots' and require improvement to achieve the expected overall sustainability performance.

Figure 2 also shows that the only HPI that met the threshold value or sustainability expectation (i.e. 5/5) was HPI 4 Social Wellbeing. One of its KPIs, which was KPI 4.1 Meeting Essential Human Needs, scored 5/5 as palm oil industries provided essential needs, i.e. water supply, health care, sanitation facilities and housing to the workers (PM 4.1.1–4.1.4). About 77% of oil palm company employees agreed that their employment has led to overall positive changes to their livelihood (Dayang Norwana et al. 2011). This showed that there was a growing realisation of the importance of workers' welfare, especially for those who work in remote locations, and also its importance for worker recruitment and retention (Gooden and Bailey 2001).

Some HPIs scored far below the threshold values due to the poor score of their PMs. In the case of HPI 5, which is an indicator for social equity scored only 1.33/5 due to the fact that one of its KPIs, 5.1 for local community empowerment and engagement, performed poorly, and hence it was considered as a social 'hot spot'. Further investigation shows that two out of three PMs under this KPI 5.1 [i.e. access to information and knowledge (5.1.1) and level of community acceptance to plantation and mill activities (5.1.3)] were ranked very low (i.e. 1/5). Another social PM (5.1.2) for Fair Partnership and Community Involvement in Decision-Making performed poorly as well (i.e. 2/5). The poor performance of these PMs was because of the fact that the communication between the oil palm industry and local community prior to the plantation development was very limited (Dayang Norwana et al. 2011). Secondly, there was a dispute regarding land acquisitions which were largely due to the lack of formal and legitimate documents (e.g. land title to prove ownership despite the natives' customary use of land) (Custodio 2017; Dayang Norwana et al. 2011; Rival and Levang 2014). Thirdly, free, prior and informed consent from the local people is not a legislative requirement for development in Malaysia.

The HPI for environmental sustainability objective—natural capital conservation, performs moderately (i.e. 3.13/5). Two of its KPIs, which meet the threshold values due to the implication of regulatory control of air, water and soil quality and industry's efforts to keep fuel cost down in operation include KPI 1.2 Air, Water and Soil Quality and KPI 1.5 Resources Consumption. However, three other KPIs on 1.1 Climate Change (2/5), 1.3 Waste Generation (2/5) and 1.4 Biodiversity (1.63/5) are identified as hot spots for the environmental objective and need a lot of improvement. KPI 1.1 Climate Change was measured by PM 1.1.1 GHG Emission of Crude Palm Oil Production. About 80% of palm oil mills in Malaysia do not have biogas facilities (Loh et al. 2017), and hence, the GHG emission to produce one tonne of CPO is still relatively high (Subramaniam et al. 2010). The hot spot in KPI 1.3 Waste Generation was caused by the generation of palm oil mill effluent and empty fruit bunches generated from the palm oil mill processes that were not recycled or reused (Abdullah and Sulaiman 2013).

The economic hot spot at HPI level was HPI 3—Sharing Economic Power as it scored 2.48/5. Its KPIs (i.e. KPI 3.2 Local community inclusion and distribution of wealth) scored only 1.96/5, mainly due to poor performance of PM 3.2.1—Employment opportunity for the local community (i.e. 1/5). This is mainly because the palm oil industry in Malaysia relies heavily on cheap foreign workers (Chow 2017).

The calculation methods used in this framework allow us to present the overall score of the assessed system in terms of sustainability gap, which is determined by the difference between the measured value and the threshold value of each indicator (Table 10). If the gap is equal to zero, the actual state of sustainability of crude palm oil production exactly matches the stakeholders' expectations or threshold value. If the gap is negative, the actual situation is not achieving expectation or the threshold value of sustainability.

An analysis was performed by first determining the gap between rank value and threshold/expectation value of PMs, i.e. 5. Then the same procedure in Table 9 was followed

Table 9 Sustainability assessment result

Sust. obj	Headline performance indicator	Key performance indicator	Performance measures	Ranking value for PM	Overall weight for PM	Score for KPI	Score for HPI	Score for sust. obj.	Score for overall sust.
Env.	1 Natural capital conservation	1.1 Climate change	1.1.1 GHG emission	2	0.0450	2.00	3.13	3.13	3.14
		1.2 Air, water and soil quality	1.2.1 NOx emission intensity from palm oil mill	5	0.0393	5.00			
			1.2.2 Biological oxygen demand of water discharged from POME pond	5	0.0447				
			1.2.3 Soil nitrate level measured through pH in waterway	5	0.0444				
		1.3 Waste generation	1.3.1 % biomass recovery/recycling	2	0.0450	2.00			
		1.4 Biodiversity	1.4.1 Plantation practice	2	0.0463	1.63			
			1.4.2 Land use	2	0.0447				
			1.4.3 Species loss	1	0.0538				
		1.5 Resources consumption	1.5.1 Fossil fuel consumption intensity (output/input energy ratio)	5	0.0415	5.00			
Eco.	2 Business continuity and resiliency	2.1 Productivity efficiency	2.1.1 Plantation yield	5	0.0476	4.50	3.75	3.12	
			2.1.2 Mill production efficiency	4	0.0485				
		2.2 Consistent profitability	2.2.1 Actual growth rate	3	0.0447	3.00			
	3 Sharing of economic power	3.1 Relative poverty	3.1.1 Average annual income per worker	3	0.0452	3.00	2.48		
		3.2 Local community inclusion and distribution of wealth	3.2.1 Employment opportunity for the local	1	0.0471	1.96			
			3.2.2 Smallholders' equity	3	0.0439				
Soc.	4 Social wellbeing	4.1 Meeting essential human needs	4.1.2 Workers' accessibility to water supply	5	0.0471	5.00	5.00	3.17	
			4.1.3 Workers' accessibility to health care	5	0.0476				
			4.1.4 Provision of sanitation facilities to workers	5	0.0474				
			4.1.5 Provision of housing facilities to workers	5	0.0460				

Table 9 (continued)

Sust. obj	Headline performance indicator	Key performance indicator	Performance measures	Ranking value for PM	Overall weight for PM	Score for KPI	Score for HPI	Score for sust. obj.	Score for overall sust.
5	Social equity	5.1 Local community empowerment and engagement	5.1.1 Access to information and knowledge	1	0.0425	1.33	1.33		
			5.1.2 Fair Partnership and Community Involvement in Decision Making.	2	0.0433				
			5.1.3 Level of community acceptance to plantation and mill activities	1	0.0444				

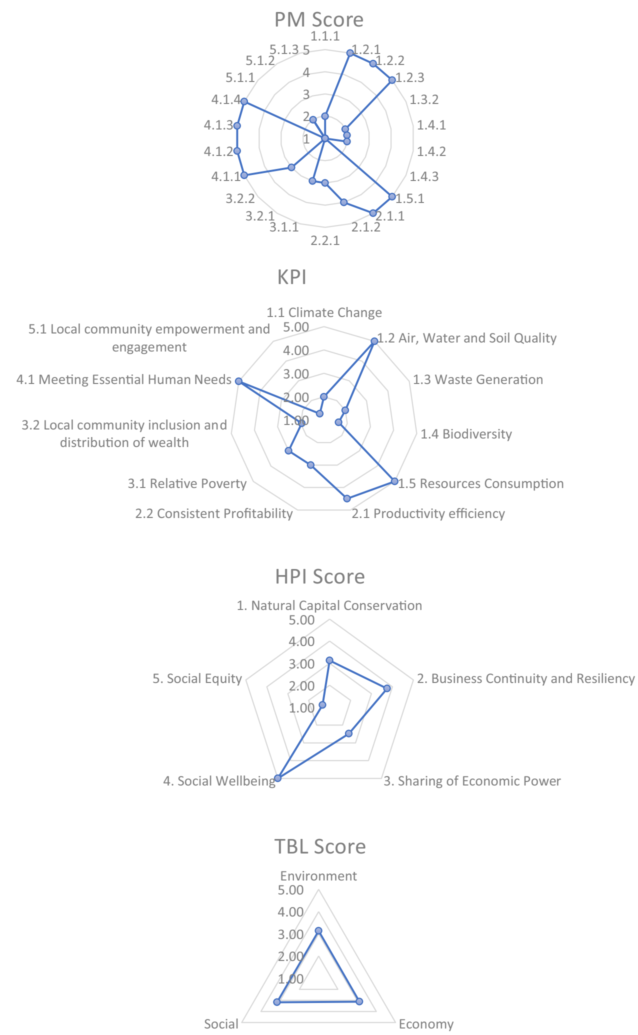

Fig. 2 Web charts of sustainability assessment result for PM, KPI, HPI and TBL objectives

using Eqs. 4, 5 and 6 to calculate the gaps for KPIs and HPIs in Table 10.

The gap of overall sustainability to threshold was − 1.86 (Table 10), which was consistent with the difference between overall sustainability score and threshold target = 3.14 − 5 = − 1.86 (Table 9).

Implications of revised framework

The revised framework further strengthens the original framework of Lim and Biswas (2015) where sustainability objectives are clearly segregated into different levels of indicators, e.g. HPI, KPI and PM. This establishes a relationship between PM and sustainability objectives. It also justifies the overall sustainability assessment score which is aggregated from PMs through a hierarchical process. The PM ranking

Table 10 Sustainability assessment results—gap between actual situation and threshold value/expectation

Sust. obj.	Headline performance indicator	Key performance indicator	Performance measures	Ranking value for PM	Gap to thresh-old	Overall weight for PM	Gap for KPI	Gap for HPI	Gap for sust. obj.	Gap for overall sust.
Env	1 Natural capital conservation	1.1 Climate change	1.1.1 GHG emission	2	− 3	0.0450	− 3.00	− 1.87	− 1.87	− 1.86
		1.2 Air, water and soil quality	1.2.1 NOx emission intensity from palm oil mill	5	0	0.0393	0.00			
			1.2.2 Biological oxygen demand of water discharged from POME pond	5	0	0.0447				
			1.2.3 Soil Nitrate Level measured through pH in waterway	5	0	0.0444				
		1.3 Waste generation	1.3.1 % biomass recov-ery/recycling	2	− 3	0.0450	− 3.00			
		1.4 Biodiversity	1.4.1 Plantation practice	2	− 3	0.0463	− 3.37			
			1.4.2 Land use	2	− 3	0.0447				
			1.4.3 Species loss	1	− 4	0.0538				
		1.5 Resources con-sumption	1.5.1 Fossil fuel con-sumption inten-sity (output/input energy ratio)	5	0	0.0415	0.00			
Eco.	2 Business continu-ity and resiliency	2.1 Productivity effi-ciency	2.1.1 Plantation yield	5	0	0.0476	− 0.52	− 1.26	− 1.89	
			2.1.2 Mill production efficiency	4	− 1	0.0485				
		2.2 Consistent profit-ability	2.2.1 Actual growth rate	3	− 2	0.0447	− 2.00			
	3 Sharing of eco-nomic power	3.1 Relative poverty	3.1.1 Average annual income per worker	3	− 2	0.0452	− 2.00	− 2.52		
		3.2 Local community inclusion and distribution of wealth	3.2.1 Employment opportunity for the local	1	− 4	0.0471	− 3.04			
			3.2.2 Smallholders' equity	3	− 2	0.0439				

Table 10 (continued)

Sust. obj.	Headline performance indicator	Key performance indicator	Performance measures	Ranking value for PM	Gap to threshold	Overall weight for PM	Gap for KPI	Gap for HPI	Gap for sust. obj.	Gap for overall sust.
Soc.	4 Social wellbeing	4.1 Meeting essential human needs	4.1.1 Workers' accessibility to water supply	5	0	0.0471	0.00	0.00	− 1.83	
			4.1.2 Workers' accessibility to health care	5	0	0.0476				
			4.1.3 Provision of sanitation facilities to workers	5	0	0.0474				
			4.1.4 Provision of housing facilities to workers	5	0	0.0460				
	5 Social equity	5.1 Local community empowerment and engagement	5.1.1 Access to information and knowledge	1	− 4	0.0425	− 3.67	− 3.67		
			5.1.2 Fair Partnership and Community Involvement in Decision Making.	2	− 3	0.0433				
			5.1.3 Level of community acceptance to plantation and mill activities	1	− 4	0.0444				

PM was ranked from 1 to 5 with level 5 as threshold value/expected performance to achieve sustainability. Gap refers to the difference between ranking value of a PM and its threshold value, e.g. if a PM scores level 3 for its performance, the gap to threshold would be 3 − 5 = − 2 system using a Likert scale allows stakeholders in the supply chain to conduct a quick self-assessment.

Comparing the original framework of Lim and Biswas (2015) ensures the quality of indicators because they were selected by involving stakeholders and area experts from 4 different backgrounds to verify the level of relevance and importance of PMs. New ideas and requests were also sought to update the list of PMs. The feedback of stakeholders and area experts has been considered to improve the structure and definition of the sustainability indicators.

The initial version of the framework considered equal weighting for all PMs (Lim and Biswas 2015), which were not supported by the stakeholders and area experts. Equal weighting for all PMs could have led to uncertainty of overall results as HPIs and KPIs were aggregated from PMs through a hierarchical process. The revised framework introduces a coefficient or weight for each PM on the basis of the level of importance voted by all participants in the survey. This approach calculates the KPI, HPI and overall sustainability score systematically. It considers not only the actual performance of PMs but also the impact that these PMs have on higher-level indicators and overall sustainability assessment results.

The ranking value of Lim and Biswas (2015) has been revised by considering the threshold values as the maximum score, which is 5. This revised scale in the assessment framework determines whether the sustainability is achieved, or threshold values are met. Threshold values as defined by Lim and Biswas (2015) (i.e. value that meets the acceptable Malaysian Government's legislative requirement, value that meets the national target set by international treaties, average oil crop's performance value and best possible performance values of existing technology (i.e. palm oil mill) that are available in the Malaysian market) were maintained for all quantitative PMs. For qualitative socio-economic PMs, the threshold value was redefined to meet the ideal socio-economic expectation (i.e. a maximum score of 5). This raised the bar of the threshold from 'reasonable performance' to 'ideal performance to meet the expectation'.

Conclusions and future works

The sustainability assessment framework for assessing Malaysian palm oil production that was initially developed by Lim and Biswas (2015) has been revised by involving key stakeholders and area experts in the selection and weighting of triple bottom line indicators. Forty participates from 4 stakeholder groups have been involved in the selection process of 22 TBL indicators for assessing the socio-economic and environmental implications of Malaysian palm oil production. Most of the PMs (i.e. 95%) of the initial framework were found relevant and important by the participants with only one being found as less relevant and less important (i.e. water consumption of plantation and production processes). As proposed by the survey participants, one new PM (species loss) was included and the criteria for ranking value of 2 PMs have been modified in this revised framework.

Apart from PM selection, this stakeholder participatory approach was applied to determine the weights of performance measures for calculating the overall sustainability score. The current approach has also redefined the ranking scale of these PMs in order to allow easier interpretation of results.

The framework would assist in the decision-making process by identifying social, economic and environmental hot spots, allowing more informed selection of appropriate strategies in order to achieve sustainability of Malaysian crude palm oil industries. The future work will consider the implementation of this sustainability assessment framework on the ground for local crude palm oil industries using old, commonly applied and state-of-the-art technologies.

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Appendix 4 – Paper 4

Lim, C.I., & Biswas W.K. (2018). Sustainability assessment for crude palm oil production in Malaysia using the palm oil sustainability assessment framework. *Sustainable Development*, 1–17. doi.org/10.1002/sd.1872 (80% contribution)

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Statement of Contribution

To Whom It May Concern,

I, Chye Ing LIM, contributed to literature review, methodology development, site data collection, results analysis, discussion and writing (80%) of the paper/publication entitled:

Lim, C.I., & Biswas W.K. (2018). Sustainability assessment for crude palm oil production in Malaysia using the palm oil sustainability assessment framework. *Sustainable Development*, 1–17. doi.org/10.1002/sd.1872

The remaining 20% of this paper/ publication was contributed by Wahidul K. Biswas.

Signature: Date: 31 March 2019

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Co-author 1: A/Prof Wahidul K. Biswas Date: 31 March 2019

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RESEARCH ARTICLE

WILEY Sustainable Development

Sustainability assessment for crude palm oil production in Malaysia using the palm oil sustainability assessment framework

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Abstract

The sustainability of production is one of the greatest challenges experienced by the Malaysian palm oil industry. Palm oil products consistently receive negative press and criticism, for causing deforestation, land use changes, peat land conversion, species loss, greenhouse gas emissions, biomass waste generation, violation of indigenous people's rights and limited local employment. This paper evaluates the sustainability of the most common crude palm oil supply chain in Malaysia, located in Sarawak, using the Palm Oil Sustainability Assessment (POSA) framework. The results show that the overall sustainability score for a typical crude palm oil supply chain in Malaysia is 3.47/5, which is below the sustainability target of 5/5. Hotspots identified include smallholder inequity, lack of biomass waste recycling and recovery, improper plantation practices, lower average wages and local employment. The site-specific application of the POSA framework in the current study demonstrates its potential to be used universally across Malaysia.

KEYWORDS

environmental management, integrated assessment, palm oil, social sustainability, sustainability assessment, sustainable development

1 | INTRODUCTION

Sustainability issues associated with palm oil production have recently received increased attention. Major palm oil customers such as BASF Nestle, Mars and Cadbury now require this raw material to be produced in a socially, economically and environmentally sustainable manner to sustain their business in the global market (BASF, 2017; Bates, 2015). Legislative changes have also put pressure on these industries to produce more sustainable palm oil. For example, the European Parliament has recently endorsed a certification scheme exclusively for palm oil products entering the European Union (EU) market, and to phase out palm oil by 2020 by using EU-grown vegetable oils for biofuel production (Chatain, 2017).

This has become a critical issue in Malaysia, where palm oil products alone contribute to 8.22% of its total export revenue (RM64.59 billion out of RM785.93 billion) in 2016 (Din, 2016; MATRADE, 2017). Being the second largest palm oil producer in the world, Malaysia needs to develop strategies to produce palm oil in a sustainable manner not only to remain competitive in the global market but also to be competitive with other oil products such as soybean oil and sunflower oil in the European, Indian and Chinese markets (Din, 2016).

To help oil palm producers address these sustainability challenges, the Malaysian Government has introduced the Malaysian Palm Oil Board (MPOB) Codes of Practice (MPOB, 2013), the *Malaysian Standard* Good Agricultural Practice (MOA, 2014) and the *Malaysian Standard* Good Manufacturing Practice (SIRIM, 2009) guidelines. Palm oil producers have also been encouraged to be MSPO (*Malaysian Standard* on Malaysian Sustainable Palm Oil) and RSPO (Roundtable on Sustainable Palm Oil) certified. Partial reimbursement of audit costs has also been offered to both large and small plantations to promote this certification scheme (MPOC, 2017).

The aforementioned guidelines and certification schemes could not help to attain the sustainability objectives of palm oil completely as they are costly, nonmeasurable, depend on principle-based criteria, and reliable and accessible data (Dizdaroglu, 2017). Ruysschaert and Salles (2014) investigated industries taking advantage of loopholes in the RSPO certification scheme. There is no achievable and systematic guideline that enables oil palm producers to comply with the standard/requirement. For example, the measurement of loss of biodiversity and greenhouse gas (GHG) emissions, which are notable impacts of oil palm production, could not be recorded due to delay associated with the lack of clarity in the guidelines. Most importantly, the certification schemes have not been effective in natural resource conservation and in changing the mindset of growers for implementing sustainability on the ground. These schemes do not even allow the industry to conduct a quick quantifiable self-assessment to identify gaps or area requiring improvement relating to sustainability.

A review of the literature shows that Life Cycle Assessment (LCA) tools have commonly been used for determining sustainability indicators of crude palm oil and palm oil biodiesel in Malaysia and neighboring countries. LCA has been used to quantify the environmental impact of palm oil production and identify hotspots for different supply chains. These LCAs measured both single impact category, mainly carbon footprint (Chase & Henson, 2010; Kaewmai, H-Kittikun, & Musikavong, 2012; Stichnothe & Schuchardt, 2011; Wicke, Dornburg, Junginger, & Faaij, 2008; Yee, Tan, Abdullah, & Lee, 2009) or multiple environmental impact indicators (Myllyviita, Holma, Antikainen, Lähtinen, & Leskinen, 2012; Subramaniam et al., 2010).

Economic impact, that is, total cost throughout the product life cycle, can be assessed through Life Cycle Costing (LCC) (Arif Dwi & Sudaryono, 2014; Ong, Mahlia, Masjuki, & Honnery, 2012; Silalertruksa, Bonnet, & Gheewala, 2012). However, LCC assesses the economic feasibility of the business, and does not consider economic implications on other stakeholders (e.g., smallholders, employers) in the supply chain. By contrast, Social Life Cycle Assessment has also been used to assess the social impact of biofuel production from palm oil (Manik, Leahy, & Halog, 2013). A comprehensive study that applied LCA to assess the environmental, economic and societal objectives (i.e., triple bottom line (TBL) objectives) of Indonesian palm oil biodiesel production was performed by Manik (2013). Nevertheless, these LCA results have not been integrated under one framework to obtain a single score of sustainability performance of palm oil industries. Also, the development of location-specific indicators for palm oil sustainability assessment has not been carried out to date (Lim, Biswas, & Samyudia, 2015).

Thus, a comprehensive sustainability assessment framework is needed to assess all processes throughout the product life cycle stages of crude palm oil production, involving the supply chain's stakeholders to identify opportunities for sustainability performance improvement (Lim et al., 2015; Teoh, 2010), and to assist in decision-making for sustainable production (Labuschagne, Brent, & van Erck, 2005). A standalone sustainability assessment framework that assesses all TBL objectives of sustainability would overcome the weaknesses discussed above. It diagnoses the causes of sustainability gaps through the use of TBL indicators to suggest relevant improvement opportunities for achieving sustainability and also to identify constraints to achieve this goal (Dizdaroglu, 2017). This framework is expected to comply with the requirement provided by Poveda and Lipsett (2011), which are "comprehensive, harmonious, habit-forming, helpful, hassle-free, hopeful, and humane."

Taking these factors into account, we have developed the Palm Oil Sustainability Assessment (POSA) framework for assessing TBL objectives of Malaysian crude palm oil production (Lim et al., 2015; Lim & Biswas, 2015, 2018). According to this framework, the TBL indicators had to be determined through a consensus conference, involving industry, academia, government and local community stakeholders. The advantages of the use of POSA framework over certification schemes, other tools and frameworks are the consideration of all dimensions of TBL, application of a structured survey method, use of multicriteria decision-making analysis, and the production of measurable and traceable results. Unlike certification schemes, the framework scientifically defined performance measures for TBL sustainability objectives and transparency has been maintained throughout the assessment process. This provides achievable outcomes and prevents ambiguity in interpreting the requirements. However, this new framework needs to be applied to assess actual palm oil sustainability performance.

Thus, this paper presents the application of Lim and Biswas' POSA framework (Lim & Biswas, 2018) to assess the actual sustainability performance of a common crude palm oil supply chain, to identify the sustainability hotspot (s) of the supply chain and to make recommendations for achieving sustainability of crude palm oil production.

2 | METHOD

Figure 1 shows the POSA framework that has been used to assess the sustainability performance of a crude palm oil supply chain. The overall sustainability performance is aggregated into Headline Performance Indicators (HPIs) for environment, economic and societal objectives. Each of these HPIs is further aggregated into Key Performance Indicators (KPIs) and then Performance Measures (PMs). Lim and Biswas (2018) defined ranking criteria for each of these PMs and proposed their weighting factors through a consensus conference.

To assess the sustainability performance of a palm oil supply chain using the POSA framework, the rankings of PMs for social, economic and environmental objectives need to be discerned by obtaining field data from the crude palm oil supply chain. The field data are compared against their corresponding ranking criteria to give them ranks on a scale of 1–5. If the calculated value of a PM has met the threshold value, then this PM is ranked 5. The gaps between the ranks of PMs and their corresponding threshold values/highest expectations (i.e., $PM_{threshold}(5) - PM_{actual\text{-}ranking}$ (>5)) are used to determine the overall sustainability gap of crude palm oil production.

Figure 2 shows the research processes, which are divided into three main stages. Preparation and planning was the first stage of the sustainability assessment, where goal and scope, as well as the system boundary of the study were determined. The most common crude palm oil supply chain in Malaysia was identified as a case study based on published statistics. Spreadsheets, forms and questionnaires were also developed following Curtin University's Research Ethics and Integrity requirements before the field survey. The second stage involves onsite data collection from all stages of the crude palm oil supply chain, calculation and ranking of both quantitative and qualitative

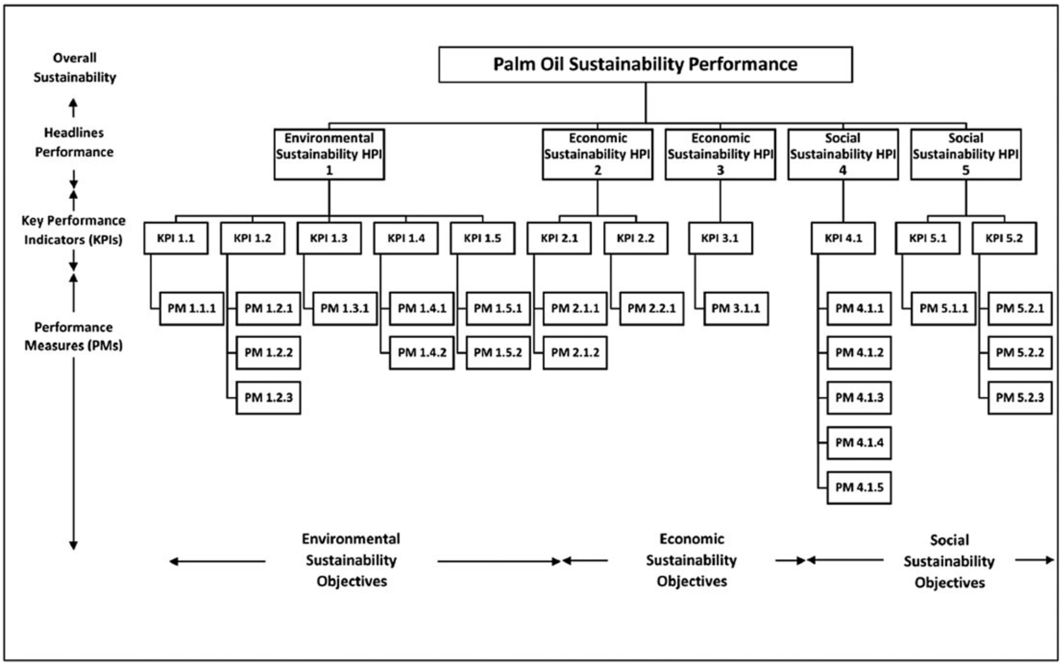

FIGURE 1 The Structure of Palm Oil Sustainability Assessment Framework (POSA) (Lim & Biswas, 2015)

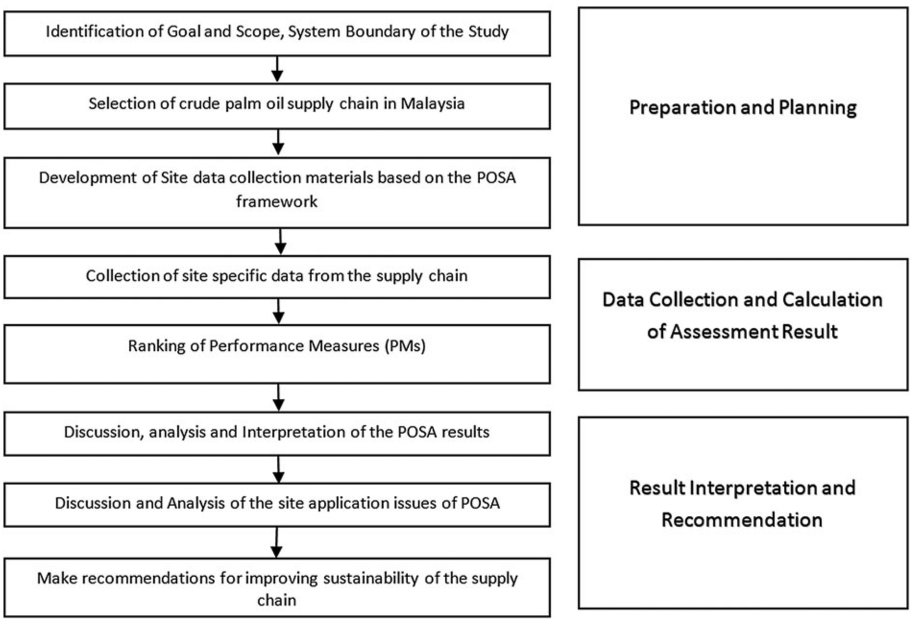

FIGURE 2 Procedure for applying sustainability assessment framework

PMs under different KPIs of the POSA framework. Finally, results were interpreted, discussed and recommendations were made for overall sustainability performance improvement for the supply chain.

2.1 | Goal and scope, system boundary of the study

The goal of the assessment is to measure how sustainable crude palm oil production in Malaysia is and to identify TBL hotspots (i.e., those PMs with large gaps) in the supply chain for developing sustainability improvement strategies. System boundary of the assessment includes all processes in the supply chain, i.e. seedling production at the nursery, production of fresh fruit bunches (FFBs) at various plantation scales and crude palm oil production at the palm oil mill (Figure 3).

2.2 | Selection of crude palm oil supply chain in Malaysia

Palm oil supply chains in Malaysia vary regarding waste management methods in oil mills (e.g., with or without a biogas capture system), source of FFBs, which could be either from independent or organized smallholders (Ismail, Arif Simeh, & Mohd Noor, 2003) or large plantation, and the type of plantation land, which can be either peatland or mineral soil land (Editor, 2013). As the study intends to apply and test

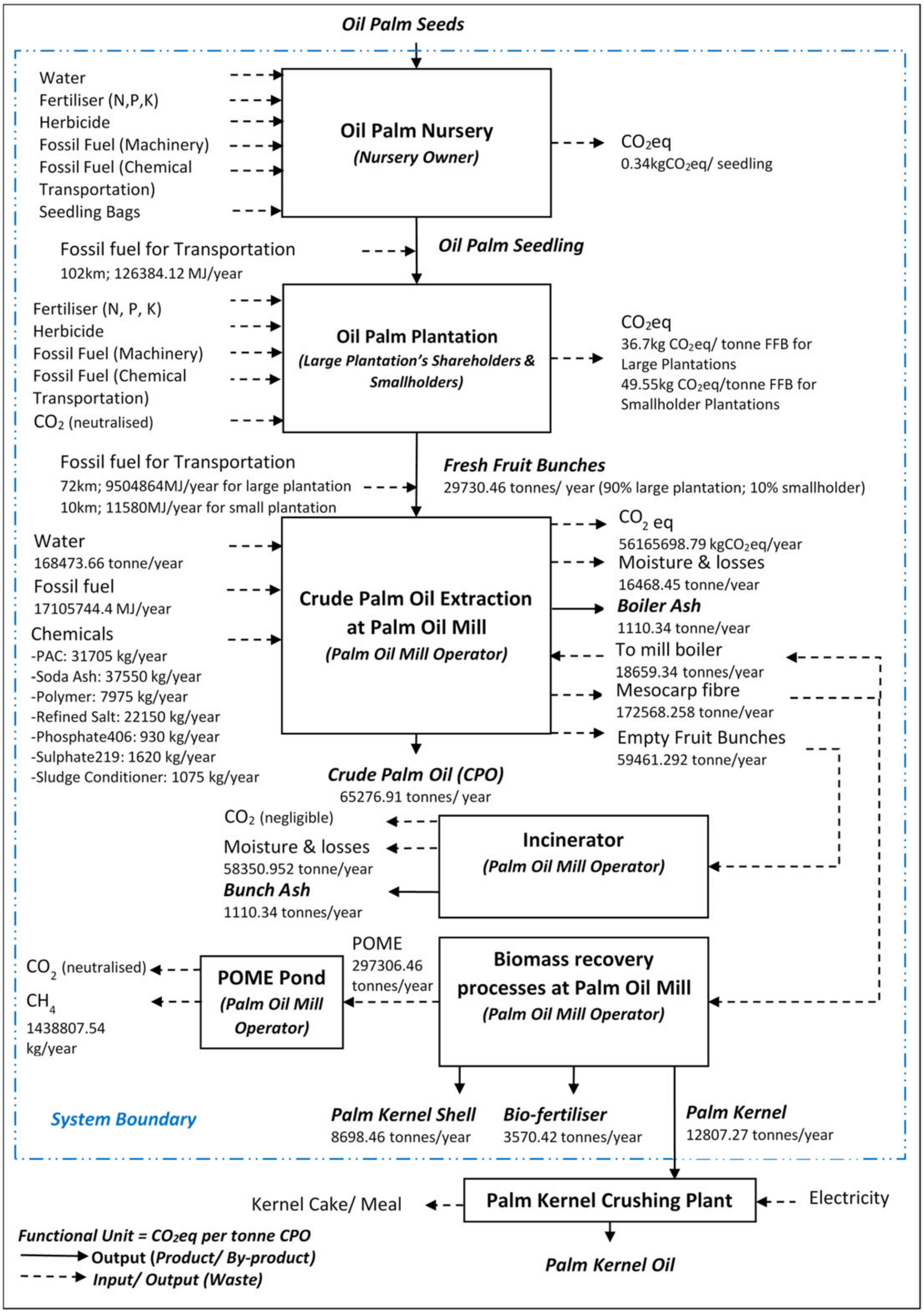

FIGURE 3 System boundary and inventory of Malaysia's most common supply chain for annual amount of crude palm oil production [Colour figure can be viewed at wileyonlinelibrary.com]

the POSA framework to assess the sustainability of crude palm oil production in Malaysia, the following statistics have been used to select the most common supply chain as a case study for this research.

Firstly, a case study site was chosen from the area where most of Malaysia's oil palm is grown. As of 2016, total oil palm plantation in Malaysia is 5,737,985 ha, where 86.7% is mature plantation (MPOB, 2017). Borneo Island (Sabah and Sarawak) alone contributes to 53.3% of plantation land in Malaysia (MPOB, 2017). Only 668,250 ha, that is, 11.65% of total oil palm plantation in Malaysia, are on peatland (i.e., 27.5% of 2.43 million ha of peatland in Malaysia were converted into oil palm plantation as of 2016 (Bernama, 2016)), while the remaining plantations are on mineral soils. Based on these statistics, a plantation on mineral soils in Borneo Island has been selected as a case study for the present research.

Secondly, the size of the plantation was selected on the basis of the distribution of oil palm plantations in 2016 by planter's category that is, private estate/large plantation, organized smallholders under government, government link agencies, for example, FELDA, RISDA, FELCRA schemes or independent smallholders (Figure 4). This distribution represents the source of FFBs for most of the palm oil mills in Malaysia, where private estate/large plantations contribute the major share (61.2%), and the remainder is supplied by smallholders (38.8%) (MPOB, 2017). Hence, the study has considered a supply chain where the FFB is sourced from both large plantations and smallholders.

Thirdly, the selection of an oil mill in the supply chain was considered. Even though the capacity of these mills varies, they have similar processes of sterilization—stripping, extraction, purification—to extract crude palm oil (MPOC, 2012). The palm oil mills are different from each other in a way that some mills are equipped with anaerobic digesters and some are not. The biogas released from the palm oil mill effluent (POME) waste is captured in this digester to avoid the emission of harmful GHGs. People in the field mentioned that there are practical difficulties associated with large-scale electricity generation from this biogas. It is of note that biogas capture and methane avoidance installation is required for new license issuance to palm oil mills that were built after January 1 2014 (MPOB, 2013). In addition, all existing palm oil mills now require these digesters to be installed by 2020 (Performance Management and Delivery Unit (PEMANDU), 2010). However, as of December 2016, of 449 palm oil mills in Malaysia (MPOB, 2017), only 92 are equipped with these biogas capture facilities (20.5%), nine are under construction (2%) and 145 are under planning (32.3%) (Loh et al., 2017). A large proprotion of the palm oil mills in Malaysia (i.e., 45.2%) do not even have plans for biogas capture facilities.

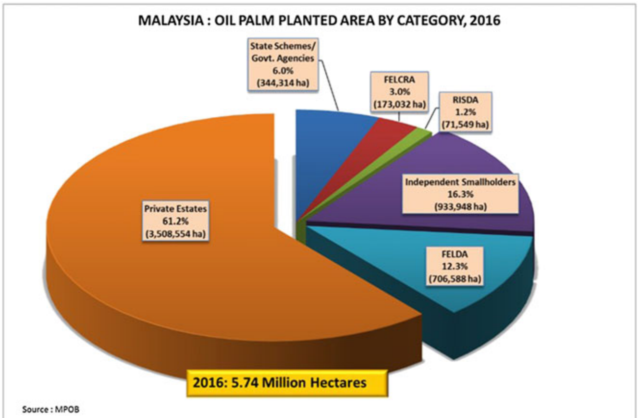

FIGURE 4 Oil palm planted area by category 2016 (MPOB, 2017) [Colour figure can be viewed at wileyonlinelibrary.com]

Therefore, the supply chain that has been chosen as a case study for the application of POSA is a crude palm oil supply chain located in Sarawak State on Borneo. The supply chain includes an MPOB-licensed oil palm nursery, both large and smallholder plantations planted on mineral soils and a palm oil mill with no biogas trapping facility/digester. The selected palm oil supply chain is shown in Figures 5 and 6, where the palm oil mill is located about 20 km away from the nearest town. The distance between the oil mill and its bulk supplier of FFBs, which is a self-owned large plantation, is about 72 km. A small proportion of FFBs or a deficit is supplied by the smallholder plantations, which are within 10 km radius of the mill. The oil palm nursery that supplies seedlings to smallholder plantations and large plantations is located about 30 km away from the palm oil mill. There is no highway in this supply chain. A public trunk road is used to connect nursery, plantations and the oil mill. The nearest town has a district office that serves the local people from 85 villages (3,453 households) (Official Website of Miri Division Administration, 2017). The key economic activities in the district are fishery and agriculture. Oil palm plantations have been flourishing over the past 10 years with the replacement of less profitable crops. A Sarawak family with a mature oil palm holding of 3 ha with an annual yield of 12 tonnes/ha has been found to have a net cash annual income of RM6,640 (i.e., USD1,660) for 150 days of labor at the plantation site, which is equivalent to RM44 (USD4.40) per day (Sujang, 2012). This is higher than the minimum wage in Malaysia.

2.3 | Development of site data collection materials based on the POSA framework

To conduct a sustainability assessment on the palm oil supply chain using the POSA framework, site-specific data need to be collected to determine the ranking of 22 performance measures (Table 1).

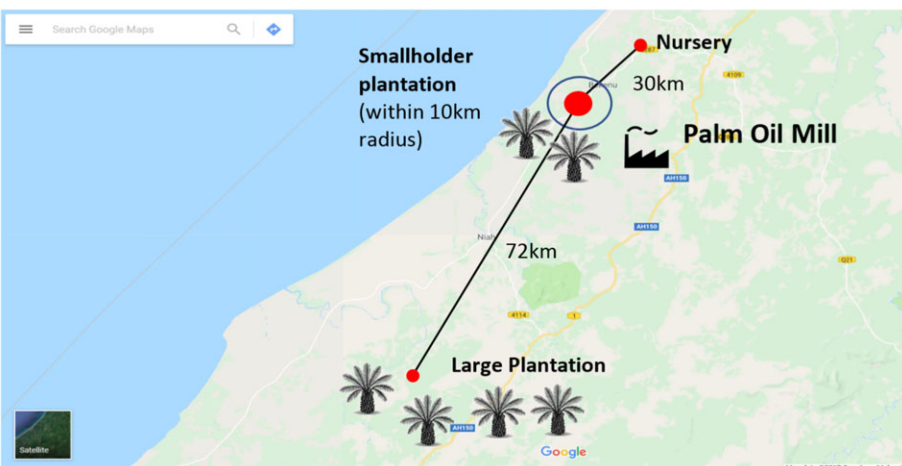

FIGURE 5 Location of the selected supply chain in Sarawak, Malaysia [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 6 Clockwise from top left- Seedlings are grown in polyethylene bags at oil palm nursery, a typical mono-culture oil palm plantation for FFB on mineral soil, fresh fruit bunches (FFB) ready for processing at the oil mill of capacity 60 metric tonne FFB per hour and the sculpture of fresh fruit bunches in the middle of the Bekenu town, Sibuti Sarawak as the symbol of the town. (Source: Field survey of this research) [Colour figure can be viewed at wileyonlinelibrary.com]

Of these 22 PMs that need to be ranked in the POSA framework, 18 are ranked on the basis of quantitative data gathered during the field survey of stakeholders in the identified supply chain, while four (i.e., 1.4.3 Species loss, 5.1.1 Sharing of information with the local community, 5.1.2 Fair partnership and community involvement in decision making, and 5.1.3 Level of community acceptance to activities of plantation and mill) were based on the collective feedback in terms of the level of expectation of the local people, who are directly and indirectly affected by the supply chain activities. Therefore, two sets of questionnaires were prepared before data collection at the site to gather quantitative and qualitative data. The first questionnaire listed all the quantitative raw data (i.e., production rate, yield, material consumption rate) that were gathered from the nursery, smallholder plantations, large plantations and palm oil mill, while the second set of questionnaires consisted of four multiple-choice questions to determine the level of expectation for four qualitative PMs. The descriptions of the multiple-choice options were prepared according to the ranking criteria of these PMs.

2.4 | Collection of site-specific data from the supply chain

The first questionnaire set was used to interview the nursery owner, smallholders, large plantations manager and palm oil mills manager of the selected supply chain to obtain raw operational data. The licensed nursery, large plantation and palm oil mill need to submit statistics to MPOB monthly and thus most operation/production data required for the assessment are readily available. Meanwhile, the data from smallholding plantations were obtained by interviewing the smallholders. The functional unit (FU) in the case is yearly crude oil production. Thus, the inputs (energy, materials) and outputs (emissions, wastes) of each life cycle stage for this FU are summarized in Figure 3.

The mass balance began from the crude palm oil production stage as it determines what amount of feedstock (i.e., FFB) is required to provide annual supply of oil and the amount of inputs (water for steam generators, diesel for backup/startup generators, and various types of chemicals including poly-aluminum chloride, soda ash, polymer, refined salt, phosphate 406, sulfate 219 and sludge conditioner, for waste water treatment processes) and wastes associated with the conversion of FFB to oil. Mesocarp fiber that remains after the crude palm oil extraction will be further processed to palm kernel and palm kernel shell as a by-product, to power the combined heat and power unit (CHP) and to produce bio-fertilizer (from decanter cake). Boiler ash produced from the combustion process at the boiler is a useful by-product that could be used as fertilizer, an additive for concrete and cement, as well as production of geopolymers (Yahya et al., 2013). The unrecovered biomass, combined with waste water from the mill processes are channeled to the open POME ponds, which release huge amounts of methane gas. Empty fruit bunches (EFBs) is another major waste from the palm oil mill. In this supply chain, the EFB is incinerated and produces bunch ash as by-product.

Once the amount of FFB is determined (297,306.46 tonnes/year), we calculated the amount of nitrogen, phosphorus and potassium (NPK) fertilizer, herbicide consumption and diesel fossil fuel combustion for machinery operation, chemical and FFB transportation that are required for the production and transportation of these FFBs to oil mills for annual crude oil production. Also, the number of seedlings (262,500 trees for large plantations and 5,000 trees for smallholder plantations) required to grow this amount of FFB and its carbon footprint per annum were calculated. Finally, the input levels for seedling production at the oil palm nursery, including water, NPK fertilizer, herbicide, polyethylene bags and diesel for machinery operation, were estimated.

The following important assumptions have been made for this case study.

TABLE 1 Site data, ranking for performance measures (PMs) and overall assessment results

Performance measures		Data from site	Ranking for PM	Overall weight for PM	Score for KPI	Score for HPI	Score for sust. Obj.	Score for overall sust.
1.1.1	GHG emission	0.814	2	0.045	2.00	2.94	2.94	3.47
1.2.1	NOx emission intensity from palm oil mill	0	5	0.0393	5.00			
1.2.2	BOD of water discharged from POME pond	22.25	5	0.0447				
1.2.3	Soil nitrate level measured through pH in waterway	92	5	0.0444				
1.3.1	% biomass waste recovery/recycling	32%	2	0.0450	2.00			
1.4.1	Plantation practice	Meet 3.5/6	2	0.0463	2.68			
1.4.2	Land use	Planted on formal agricultural land	3	0.0447				
1.4.3	Species loss	12% voted 1, 5% voted 2, 39% voted 3, 34% voted 4, 10% voted 5	3	0.0538				
1.5.2	Energy (fossil fuel and biomass) consumption intensity (output–input energy ratio)	7.65	3	0.0415	3.00			
2.1.1	Plantation yield	25.55	5	0.0476	5.00	4.50	3.13	
2.1.2	Mill production efficiency	0.2196 tonnes/tonne FFB	5	0.0485				
2.2.1	Actual growth rate	−4%	4	0.0447	4.00			
3.1.1	Average annual income per worker	26.95	2	0.0452	2.00	1.76		
3.2.1	Employment opportunity for locals	31.33	2	0.0471	1.52			
3.2.2	Smallholders' equity	10%	1	0.0439				
4.1.1	Workers' accessibility to water supply	100%	5	0.0471	5.00	5.00	4.34	
4.1.2	Workers' accessibility to health care	100%	5	0.0476				
4.1.3	Provision of sanitation facilities to workers	100%	5	0.0474				
4.1.4	Provision of housing facilities to workers	100%	5	0.0460				
5.1.1	Sharing of information with the local community	32% voted 1, 10% voted 2, 36% voted 3, 22% voted 4, 0% voted 5	3	0.0425	3.68	3.68		
5.1.2	Fair partnership and community involvement in decision-making	19% voted 1, 20% voted 2, 29% voted 3, 27% voted 4, 5% voted 5	3	0.0433				
5.1.3	Level of community acceptance to plantation and mill activities	85% agreement	5	0.0444				

The weight for each PM is derived from its level of importance and the level of relevance voted by the four groups of stakeholders of palm oil production, including industry, authority, local community, activists and academia (Lim & Biswas, 2018).

FFB, fresh fruit bunches; HPI, Headline Performance Indicator; KPI, Key Performance Indicator; PM, Performance Measure; POME, palm oil mill effluent.

1. The production and transportation (supplied by FELDA) of oil palm seeds are excluded as this is a sort of fill-in and fill-out process in which some portion of oil palm produced is used as seed.
2. The life span of a palm tree has been conservatively considered to be 25 years based on estimates provided by plantation companies and literature (Wilmar, 2018; Woittiez, van Wijk, Slingerland, van Noordwijk, & Giller, 2017).
3. The fuel consumption of a 10-tonne truck has been considered as 30 L/100 km (Sharpe & Muncrief, 2015).
4. It was assumed that the trucks are fully loaded with FFB when they are transported to the oil mill.
5. The weight of EFB has been considered as 20% that of FFB (Chang, 2014).
6. CH_4 (or CO_2 equivalent) generated from POME biogas is neutralized with CH_4 sequestered from oil palm plantations (Wicke et al., 2008).
7. CO_2 emissions from mill steam generation and EFB incineration are excluded because the CO_2 emissions from biomasses are considered as biogenic or sequestered by plants (Kaewmai et al., 2012; Klaarenbeeksingel, 2009)
8. Global warming potential for a 100-year time horizon has been considered for calculating CO_2 equivalent GHG emissions as recommended by the Intergovernmental Panel on Climate Change (IPCC) th Assessment Report (AR5), where 1 CH_4 = 28 CO_2eq and 1 N_2O = 265 CO_2eq (Intergovernmental Panel on Climate Change, 2014)
9. Due to the absence of local databases, the emission factors (EFs) of inputs in the inventory have been obtained from the IPCC Emission Factor Databases (IPCC, 2017), BioGrace standard value (Biograce, 2011) and other literature on palm oil LCA in Malaysia and surrounding countries (Chunyan, Dawei, Yanling, Yujie, & Man Sing, 2015; Wicke et al., 2008; Yasutoshi, Kanako, Mari, & Kyosuke, 2012).

The second questionnaire was used to interview village heads and the local community around the mill and plantations. Forty-one representatives from 85 villages were interviewed. These interviewees/respondents are directly affected by the activities of the palm oil supply chain, such as smallholders and residents of villages near the palm oil mill and plantation. The interview was conducted in the local language to ensure the questions and choices of ranking criteria were understood. The PMs were ranked based on the collective feedback from these interviewees. Apart from these four questions, the questionnaire also has provision for interviewees to provide constructive feedback on palm oil production activities surrounding them.

2.5 | Ranking of performance measures

Once the PMs are calculated using field data, the ranking values for PMs, KPIs, HPIs and overall sustainability performance are calculated following Lim and Biswas (2018) (Table 1).

The threshold value for each PM is given the highest rank 5, which sets a performance target for the supply chain to produce crude palm oil in a "sustainable" manner (Lim & Biswas, 2018). The results show that three environmental PMs—1.2.1 NOx emission intensity from palm oil mill, 1.2.2 BOD of water discharged from POME pond, 1.2.3 Soil nitrate level measured through pH in waterway— and two economic PMs—2.1.1 Plantation yield and 2.1.2 Mill production efficiency—met the threshold criteria. Three of these PMs (1.2.1, 1.2.2, 1.2.3) are actually the standard parameters that any palm oil supply chain must meet under the regulations set by the Department of Environment. These parameters are usually measured by the third-party and certified auditor before submission to the local authority.

Similarly, five social PMs also met threshold criteria: all four PMs 4.1.1–4.1.4 under KPI 4.1 of Meeting essential human needs and 5.1.3 Level of community acceptance to plantation and mill activities.

The plantation yield of the selected supply chain is 25.55 tonnes FFB/ha, which is higher than the national average of 15.91 tonnes/ha in 2016 (MPOB, 2017). This is because the plantation reached peak production after 10 years. Studies confirmed that the highest yield of oil palm usually takes place between 6 and 10 years (Darmawan, Takeuchi, Haryati, R Najib, & Na'aim, 2016). Other factors for this high yield are better soil characteristics, and growth under lower temperature and higher rainfall zone (Shanmuganathan & Narayanan, 2012; Woittiez et al., 2017). In addition to increased yield, the crude oil production efficiency of the oil mill in the selected supply chain is 0.2196 tonnes crude palm oil (CPO) per tonne FFB (21.96%), which is also slightly higher than the national average of 20.18% in 2016 (MPOB, 2017). This higher performance is due to better grade control of FFB received at the mill, and the practice of smallholder support schemes, where bio-fertilizer produced from the palm oil as a by-product in the mill are given free to smallholders to improve their FFB quality. As a result, the oil yield for crude palm oil is 5.61 tonnes/ha/year, which is much higher than soybeans (0.5 tonnes/ha) and rapeseed (2 tonnes/ha) (Zimmer, 2010).

Five of seven PMs of social sustainability objectives met the threshold values: both palm oil mill and plantation site have prepared basic facilities due to their remote location, such as housing, electricity and water supply, healthcare access and sanitary services for their workers, which have cut down on living costs. This is supported by the fact that the local community showed a high level of acceptance (85% agreement) toward the palm oil production activities, despite their diverse opinions regarding other environment and social PMs such as species loss, information sharing and fair partnership. The feedback collected from the local community is shown in Figure 7.

Twelve PMs perform below the threshold levels as there are differences between their actual ranking and the threshold values, which are gaps (Table 2). A larger gap means that more improvement is needed to attain the threshold value or performance target of that PM. The environmental objectives have gaps in PMs of 1.1.1 GHG emission, 1.3.2 Percentage of biomass recovery/recycling, 1.4.1 Plantation practice, 1.4.2 Land use, and 1.4.3 Species loss. The gaps of economic PMs are found in 2.2.1 Actual growth rate, 3.1.1 Average annual income per worker, 3.2.1 Employment opportunity for locals, and 3.2.2 Smallholders' equity. For social PMs, 5.1.1 Sharing of information with the local community and 5.1.2 Fair partnership and community involvement in decision-making do not meet the threshold.

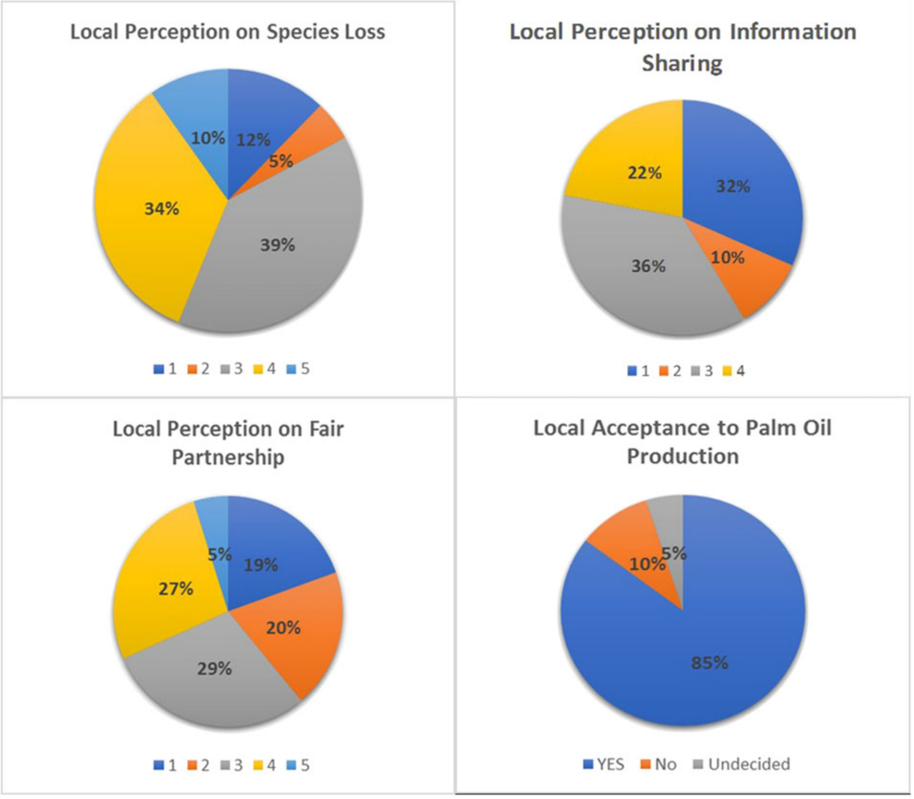

FIGURE 7 PMs based on expectation of the community [Colour figure can be viewed at wileyonlinelibrary.com]

3 | INTERPRETATION OF RESULTS AND RECOMMENDATIONS

3.1 | Triple bottom line implications of crude palm oil production

Figure 8 presents the gaps among PMs, KPIs, HPIs and TBL objectives. The crude palm oil production supply chain has smaller gaps for societal aspects than for environment and economic aspects. These gaps discern the level of sustainability performance and suggest opportunities for improvement, which are discussed below.

3.1.1 | Social bottom line assessment

The crude palm oil supply chain performs better for societal aspects than for economic and environmental aspects (Figure 8a). The gap for societal HPI is −0.66 smaller than the gaps for economic (−1.87) and environmental (−2.06) aspects (Figure 8b), mainly because the crude palm oil business model meets the requirement of KPIs of social wellbeing by offering essential living needs to its workers (Figure 8c). The provision of housing, sanitary, healthcare facilities and water supply in fact closes the gap of PMs 4.1.1–4.1.4. However, there exists a gap between the HPI value of social equity and expected value (Figure 8b) as there is a need to improve the KPI for local community empowerment and engagement by sharing information with the local community (i.e., PM 5.1.1) and there is a need to offer fair partnership to the local smallholders and land owners, and to involve this local community in the decision-making process for activities that affect them (i.e., PM 5.1.2) (Figure 8d).

For PM 5.1.1, it appears from the interview that the information needs to be shared between plantation, mill and the local people and made transparent and available to communities who are affected in the palm oil supply chain. Information relating to commencement and expansion of plantation and mill development, mill emissions and effluent discharge is not provided adequately to local people in a timely manner. A large proportion of locals (i.e., 36% of the respondents interviewed) received information on land clearance before he plantation and mill development, but nothing except for information on daily FFB rate was disseminated during the operation to collect fruits from the stakeholders. By contrast, about 32% of the interviewees did not receive any information from the plantation owners and mill operator throughout all stages of plantation and mill development. This shows a significant communication breakdown between the palm oil supply chain and local stakeholders, where local people with less influence are found to be less involved and informed in the development of the project.

In the case of PM 5.1.2 for fair partnership and community involvement in decision-making, only 5% of the interviewees acknowledged that free, prior and informed consent (FPIC) was considered as mandatory in any activities of the supply chain that could potentially affect them, and also confirmed that their land is used through fair and legally binding agreement, 19% stated they are not involved at all in decision -aking, and were not consulted on land use issues, and 20% confirmed that there is an indirect channel to provide feedback to the industry but there is no FPIC on land use. Many of the interviewees (29%) agreed that there is no FPIC for some activities in the supply chain that could potentially affect them physically and financially. However, they agreed that the local community are able to

TABLE 2 Results of gap analysis (Lim & Biswas, 2018) for site application of POSA framework on crude palm oil

Sustainability objectives	Headline performance indicator	Key performance indicator	Performance measures	Ranking value for PM	Gap to threshold	Overall weight for PM	Score for KPI	Score for HPI	Score for sustainability objective	Score for overall sustainability
Environment	1 Natural capital conservation	1.1 Climate change	1.1.1 GHG emission	2	−3	0.0450	−3.00	−2.06	−2.06	−1.53
		1.2 Air, water and soil quality	1.2.1 NOx emission intensity from palm oil mill	5	0	0.0393	0.00			
			1.2.2 BOD of water discharged from POME pond	5	0	0.0447				
			1.2.3 Soil nitrate level measured through pH in waterway	5	0	0.0444				
		1.3 Waste generation	1.3.2 % biomass recovery/recycling	2	−3	0.0450	−3.00			
		1.4 Biodiversity	1.4.1 Plantation practice	2	−3	0.0463	−2.32			
			1.4.2 Land use	3	−2	0.0447				
			1.4.3 Species loss	3	−2	0.0538				
		1.5 Resources consumption	1.5.1 Energy (fossil fuel and biomass) consumption intensity (output/input energy ratio)	3	−2	0.0415	−2.00			
Economy	2 Business continuity and resiliency	2.1 Productivity efficiency	2.1.1 Plantation yield	5	0	0.0476	0.00	−0.50	−1.87	
			2.1.2 Mill production efficiency	5	0	0.0485				
		2.2 Consistent profitability	2.2.1 Actual growth rate	4	−1	0.0447	−1.00			
	3 Sharing of economic power	3.1 Relative poverty	3.1.1 Average annual income per worker	2	−3	0.0452	−3.00	−3.24		
		3.2 Local community inclusion and distribution of wealth	3.2.1 Employment opportunity for locals	2	−3	0.0471	−3.48			
			3.2.2 Smallholders' equity	1	−4	0.0439				
Social	4 Social wellbeing	4.1 Meeting essential human needs	4.1.1 Workers' accessibility to water supply	5	0	0.0471	0.00	0.00	−0.66	
			4.1.2 Workers' accessibility to health care	5	0	0.0476				
			4.1.3 Provision of sanitation facilities to workers	5	0	0.0474				
			4.1.4 Provision of housing facilities to workers	5	0	0.0460				
	5 Social equity	5.1 Local community empowerment and engagement	5.1.1 Sharing of information with the local community	3	−2	0.0425	−1.32	−1.32		
			5.1.2 Fair partnership and community involvement in decision-making.	3	−2	0.0433				
			5.1.3 Level of community acceptance to plantation and mill activities	5	0	0.0444				

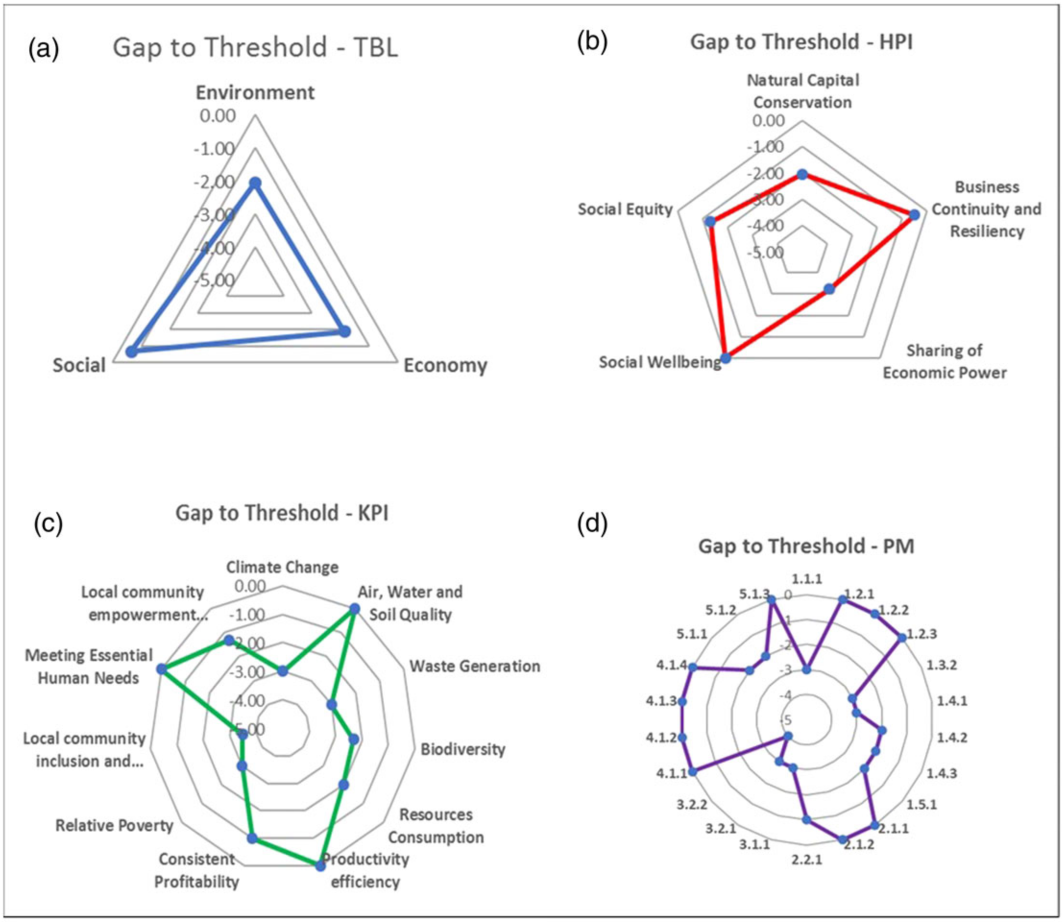

FIGURE 8 Sustainability outcomes using the POSA framework a) TBL Objectives b) HPIs c) KPIs and d) PMs [Colour figure can be viewed at wileyonlinelibrary.com]

provide their opinion to plantations and mill owners through a readily available channel, that is, community leaders and village heads, on any issues affecting them. The survey concludes that land use issues remain for at least 29% of the interviewees, and only a part of the community is consulted in the decision-making discussions.

Despite the lower level of expectations for PMs 5.1.1 and 5.1.2, a significant portion of the local people (85%) have supported the development of palm oil production in their area as this business has brought additional income to the local people though job creation. Regardless of whether the local people supported or opposed this business, the common concern was on the environmental consequences of palm oil production.

3.1.2 | Environmental bottom line

Environmental objectives showed the largest gap (i.e., −2.06) between the actual performance and the required level of environmental sustainability compared to those for economic and social objectives (Figure 8a). Natural capital conservation is the only HPI of the environmental objective and most of its KPIs, including climate change, waste generation, biodiversity and resource consumption, did not meet the threshold value (Figure 8c). The PMs of these KPIs show that there are gaps in 1.1.1 GHG emission (−3.00), 1.3.1 percentage of biomass waste recovery (−3.00), 1.4.1 plantation practice (−3.00), 1.4.2 land use (−2.00), 1.4.3 species loss (−2.00) and 1.5.1 output/input energy ratio (−2.00) (Figure 8d).

GHG emissions from the crude oil supply chain is 0.814 tonnes CO_2eq/tonne CPO, which is 442.67% higher than the threshold value (i.e., 0.15 tonnes CO_2eq/tonne CPO by 2020). This is mainly because of the absence of biogas capture facilities as the POME alone contributes to a significant portion of GHG emissions (i.e., 75.86%, 33.6 m^3 CH_4/tonne CPO) (Wicke et al., 2008). For PM 1.3.1 on percentage of biomass waste recovered/recycled under the KPI of 1.3 Waste generation, there exists a gap as only 41% of the biomass waste is recycled, mainly for cogeneration in the CHP unit. Part of this waste is recovered as a by-product (i.e., palm kernel, palm kernel shell, bunch ash and boiler ash), as well as for use as bio-fertilizer. A significant portion of the biomass waste (59%) went to the POME pond producing methane. Methane is a powerful GHG, 28-fold more so than CO_2 (IPCC, 2014).

Apart from PMs 1.1.1 and 1.3.1, the PMs under KPI 1.4 of Biodiversity also perform poorly (Figure 8c), because PM 1.4.1 (i.e., plantation practice) only met 3.5 of the six plantation practice requirements. Under current plantation practice, landscape heterogeneity was not considered in large-area planting to optimize planting area. Secondly, integrated pest management or integrated livestock farming was not in place to reduce herbicide and pesticide consumption. Thirdly, synthetic fertilizers are still heavily used as the main source of nutrients for oil palm and there is only very limited use of organic fertilizers.

Another underperformed PM under KPI 1.4 of Biodiversity is 1.4.2 Land use. The POSA framework sees the type of land use as an important factor affecting the biodiversity conservation (e.g., oil palm plantation replacing peat land or high conservation value forest would directly lead to biodiversity loss and hence is given a rank value of 1). The threshold criterion for this PM is defined as replantation on the existing site by applying the concept of agricultural intensification. In this case study, the oil palm trees of large plantations were replanted on agricultural land and did not replace forest or peatland of high conservation value. However, best agricultural management and agricultural intensification were not practised, as oil palm monoculture still exists at plantations. Monoculture reduces biodiversity, eliminates natural biological control, changes organism resistance, leads to soil degradation and hence increased demand for synthetic fertilizers, herbicides and pesticides over the time causing ultimately acidification and eutrophication impacts (Regenerative, 2014; Vijay, Pimm, Jenkins, & Smith, 2016). Also the feedback that was received from the local community regarding PM1.4.3 confirms that there was species loss following development of palm oil and the required levels of conservation (e.g., riparian reserve for oil palm plantation (SALCRA, 2016)) have note been made to date.

The PM 1.5.2 Energy (fossil fuel and biomass) consumption intensity (i.e., under KPI 1.5 on resource consumption), which is measured as output/input energy ratio, shows that there is room for improvement in terms of total amount of energy input to the supply chain (Figure 8c). The energy output/input ratio of the selected supply chain has been estimated as 7.65, which is 15% lower than the threshold value. The value is calculated by dividing the total energy produced from the key product (ie, energy from CPO and palm kernel (MJ/year)) over total energy input to the supply chain (ie, fossil fuel and biomass energy input to the nursery, plantations and mill (MJ/year)). While plantation yield and mill production efficiency have met the threshold value, other improvement considerations such as the use of cleaner fuel, fuel-efficient transportation and improved efficiency of the mill's CHP unit need to be considered to further reduce the energy input and to increase energy consumption intensity.

3.1.3 | Economic bottom line

There is a large gap between the actual performance and the required level of economic sustainability mainly due to the poor performance of HPI 3, which is the sharing of economic power. HPI 2, business continuity and resiliency, with a gap of −0.5 performs far better than HPI 3, sharing of economic power, with a gap of −3.24 (Figure 8b). The former is slightly further from the target value as its PM 2.2.1 on actual growth rate of the crude palm oil mill business is slightly lower than the sustainable growth rate. The mill was operating slightly under its capacity due to shortage of FFB supply in the market as a result of labor shortage and adverse weather conditions (i.e., drought due to El Niño) (Wong, 2016; Zainul, 2017). This literature-based interpretation is consistent with the feedback received from the interviewees.

A large gap was found for HPI 3 on sharing of economic power because the PMs of KPIs on relative poverty and local community inclusion and distribution of wealth have very low scores (i.e., 2 and 1). PM 3.1.1 shows that the average annual income per worker in the supply chain is only 27% of the national median income in 2016, which is below the relative poverty line defined at 50% of the national median income (OECD, 2016). Besides, the crude palm oil supply chain employed only 31% of local staff and sourced only 10% of its FFB from smallholders, leading to low performance of PMs, including PM3.1.2—employment opportunity for locals—and PM 3.1.3—smallholder equity.

3.2 | Identifying causes of hotspots

The sustainability hotspots of the supply chain that were identified at PM level are PM3.2.2 smallholder equity (Gap = −4), PM3.1.1 average annual income of workers (Gap = −3), 3.2.1 employment for locals (Gap = −3), PM1.1.1 GHG emissions (Gap = −3), PM1.3.2 percentage of biomass waste recycling and recovery at the mill (Gap = −3) and PM1.4.1 plantation practice (Gap = −3).

The following factors have led to low smallholder equity in palm oil production. First, most of the palm oil mill operators in Malaysia have their own large plantation to ensure a guaranteed supply of FFB for oil production and to secure financial stability. These palm oil mills source FFB from smallholder plantations only to meet any deficits. Secondly, there will be additional overheads associated with FFB collection, grading and payment process if FFBs are sourced directly from smallholders. Thirdly, FFBs produced from smallholder plantations are not always of the required quality (i.e., FFBs of lower grade are mixed with higher grade) due to financial and resource constraints of the smallholders, and thus there has been a lower oil yield of FFB compared to that produced in well-managed large plantations.

The average income of workers along the CPO supply chain is RM1409 (USD352.25 for exchange rate of RM4 to 1USD), which is higher than the national minimum wage in East Malaysia (i.e., RM920 [USD230] and RM1000 [USD250] in West Malaysia) (Kannan, 2017). However, the POSA framework evaluates relative poverty rather than absolute poverty, which reflects better on wealth distribution (Lim & Biswas, 2015). Therefore, the average income of workers is in fact below the relative poverty line although the business owners of the supply chain have offered wages that are higher than the minimum national limit.

Labor supply to the CPO supply chain, particularly for nursery and plantations, depends heavily on foreign workers. This is because low wages plus heavy manual work makes the job less attractive to local people. The managerial and other administrative positions along the supply chain (eg, managers, engineers, office administrators and supervisors) are usually filled by local people but they only contribute to about 30% of the workforce (31.33% in this case study). Hence, PM3.2.1 on local employment could not meet the threshold value. The dependency on foreign workers creates risk to the palm oil supply chain, as a change of foreign worker policies could lead to serious labor shortages for the industry (Chow, 2017). The influx of foreign workers could also lead to various social issues, such as a rise in criminal activities and illegal workers (Abdul-Rahman, Wang, Wood, & Low, 2012; *Borneo Post*, 2017). The employment of low-waged foreign workers in the supply chain would also lead to questions of exploitation for business gain. Social justice and equity are nondiscriminatory between local and foreign labors.

PM 1.3.2 Biomass waste recovery at the palm oil mill is less than 50% of the waste generated. A large amount of POME is generated from the mixture of unrecovered mesocarp fiber waste and water consumed in the milling process (mass balance at the palm oil mill is shown in Figure 3). To increase the percentage of waste recovery, either the amount of mesocarp fiber needs to be reduced, or the amount of waste recovery rate must be increased. With current technology, there is a limitation (specify) to increasing mill efficiency to reduce biomass waste generation. A more feasible choice could be to increase the recovery of biomass waste from mesocarp fiber. In this supply chain, the mill recovers biomass waste from mesocarp fiber in the form of palm kernel, palm kernel shell and bio-fertilizer. Part of the mesocarp fiber also goes to the cogeneration process to produce steam and electricity for the mill. Boiler ash from the steam boiler and bunch ash from EFB incineration are two other biomass by-products from the mill. The remaining waste become POME. POME waste is also the root cause of hotspot PM 1.1.1—GHG emission—because of high methane gas emission from its aerobic and anaerobic treatment ponds.

One of the methods of POME waste management is the installation of a biogas digester. Although a regulatory requirement has been introduced, the majority of palm oil mills are yet to comply. This is mainly due to the high capital cost of the biogas digester. Another important factor is the lack of a symbiotic industrial network for the biogas generated. The interviewee explained that palm oil mills are mostly located at remote locations and generate electricity independently from the grid. The CHP unit in the mill is sufficient to supply total energy needs for the mill, while auxiliary facilities and staff housing using biomass waste, that is, mesocarp fiber as fuel. The Sarawak state of Malaysia does not have a fit-in-tariff scheme, and it will not be financially viable to construct a distribution system, connecting the mill to the main grid (*Borneo Post*, 2014). The palm oil mill is surrounded only by palm oil plantations and there is no other mill or factory nearby where this additional energy can be sold. Therefore, the additional biogas generated from the biogas capture facilities is not needed for either internal consumption or meeting demand of the external customers. Because there is no financial incentive, this discourages the mill operator of this supply chain from building a biogas digester. In fact, of 86 palm oil mills in Malaysia that have installed a biogas digester, 56% do not use the biogas but instead burns it (Loh et al., 2017).

The supply chain had in fact adopted some effective plantation practices required in the POSA framework, including the use of certified seedlings and zero burning principle in plantation, provided clear plantation boundaries/landscape mapping and reduced synthetic fertilizer consumption by partially applying bio-fertilizer. However, complete replacement of synthetic fertilizer with bio-fertilizer was avoided to attain the required yield of oil palm. For the same reason, other recommended plantation practices, including patch planting/successive strips and connectivity/variable rotation to increase

TABLE 3 Sustainability improvement strategies

Sustainability hotspots	Gap to threshold	Sustainability improvement strategies
1.1.1 GHG Emission	−3	Capture methane gas from POME waste through biogas capture system Eliminate diesel consumption for diesel engine (use for start-up and emergency) (EF = 0.088 CO_2eq/MJ) with bio-gas powered engine EF = 0.013 CO_2eq/MJ) (IPCC, 2017). Evaluate feasibility of storing biogas in bottle cylinder as compressed biomethane (CBM) (Dussadee, Reansuwan, & Ramaraj, 2014; Yang, Ge, Wan, Yu, & Li, 2014) to promote installation of biogas digester and avoid flaring of unused biogas. Reduce emission from EFB incinerator by other cleaner waste management methods e.g. produce EFB shredded fibre for pallet biofuel or fibre mat. Reduce fossil fuel for transportation by sourcing from plantations at closer proximity. Reduce fossil fuel consumption for transportation by partially replace diesel with biogas in duel-fuel engine Replace all/more synthetic fertilizers with organic fertilizers which can be digested slurry coming out from the biogas digester.
1.3.2 % biomass recovery/recycling	−3	Increase the percentage of biomass recovery by POME waste recycling through biogas production from anaerobic digester (Poh & Chong, 2009), and providing nutrient source to culture microalgae for biodiesel and bioethanol production (Lam & Lee, 2011; Tang et al., 2011) Reduce overall biomass waste generation by improving mill production efficiency at every product (i.e. CPO, palm kernel, palm kernel shell) extraction process. Average Oil Extraction Rate (OER) in 2016 for Malaysia ranged from 19.22% to 21.11% (average = 20.18%). While the OER could largely factored by quality of FFB received, it could be improved through technologies e.g. residual oil recovery system (0.15–0.45% oil recovery per tonne FFB) (Subramaniam, Menon, Sin, & Choo, 2013). Palm kernel and palm kernel shell recovery could also be improved by adding additional cyclone separation process (Ismail, 2010)
1.4.1 Plantation Practice	−3	Replace all/more synthetic fertilizers with organic fertilizers produced from decanter cake (Haron, Mohammed, Halim, & Din, 2008) and biogas digester slurry (Rahayu et al., 2015) Implement integrated pest management (Caudwell, 2000) and integrated livestock farming (Gabdo & Bin Abdlatif, 2013) at plantations to reduce pesticide and herbicide consumption.

(Continues)

TABLE 3 (Continued)

Sustainability hotspots	Gap to threshold	Sustainability improvement strategies
		Introduce patch planting/successive strips and connectivity/variable rotation at plantations to increase landscape heterogeneity (Azhar et al., 2015)
1.4.2 Land Use	−2	Introduce best management practice such as obtain seed with high yield potential from certified seed producers to improve plantation yield (Donough, Witt, & Fairhurst, 2009) Practise agricultural intensification through land sparing i.e. practise high-yield agriculture and spare land for conservation of natural habitat (Law et al., 2015; Phalan, Onial, Balmford, & Green, 2011) to improve biodiversity (Devendra, 2009) and increase total yield from land.
1.4.3 Species Loss	−2	Increase biodiversity through the practise of agricultural intensification at plantations i.e. increase production and spare land for species conservation (Law et al., 2015), and practise integrated livestock farming to promote agrobiodiversity. Increase wildlife and species conservation through land planning, riparian reserves and forest reserve.
1.5.1 Energy consumption intensity (Output/ Input energy ratio)	−2	Reduce fossil fuel for transportation by sourcing from plantations at closer proximity. Reduce fossil fuel consumption for transportation by partially replace diesel with biogas in duel-fuel engine Improve energy efficiency of processes at mill to reduce diesel and biomass fuel consumption (e.g. improve boiler efficiency. Eliminate diesel consumption for diesel engine (use for start-up and emergency) with bio-gas powered gas engine.
2.2.1 Actual Growth Rate	−1	Increase palm oil mill total production by sourcing more FFB from smallholders to make up the deficit. Implement smallholder support schemes to help local smallholders improve quality of FFB through training program, supply of quality seedling and organic fertilizers. Offer better FFB rate to encourage investment from local people in smallholding plantations and supply of FFB to the supply chain.
3.1.1 Average annual income per worker	−3	Review salary scale of workers, particularly plantation workers to reduce relative poverty.
3.2.1 Employment opportunity for the local	−3	Review salary remuneration package of employees, particularly plantation workers to encourage local employment. Increase the overall benefits for the workers through innovation in staffs' incentives e.g. share options, plantation/mill improvement projects, to encourage local employment.
3.2.2 Smallholders' equity	−4	Increase FFB sourced from smallholders by introducing smallholder development/ support programme, to provide financial support/partnership schemes to the smallholders and therefore improve reliability of FFB supply from them. Engage local smallholder through education and training scheme to help them producing good quality FFB. Increase of knowledge exchange and improve social capacity is said to help with smallholders' adaptive capacity to climate change (Borsky & Spata, 2017)
5.1.1 Sharing of information with the local community	−2	The supply chain should first link community investment (i.e. allocation of fund for community engagement activities) to business objectives so that it acknowledges the value of community engagement. The supply chain could then build a strong stakeholder engagement process by identifying the stakeholders and their representative, forming a stakeholder management team, and develop a stakeholder engagement plan to manage stakeholders' expectations, resolve conflict e.g. land issues and establish methods of communication and reporting (Arsenova, Nyhan-Jones, Bottriell, & Pollett, 2015). Communication and reporting could be done through regular meetings/dialogue with the local people to update any activities that could potentially affect them. Press release could ensure the information reaches out to more people.
5.1.2 Fair partnership and community involvement in decision making.	−2	FPIC is defined as consent among all stakeholders, including investors, companies, indigenous peoples, and the local communities, resulted from informed, noncoercive negotiations that occur prior to the proposed activity (RSPO, 2007) Obtaining FPIC shall be considered mandatory prior to any activities and development, particularly in cases where land disputes occur. It is suggested that FPIC should be sought throughout the plantation cycle at every stage of the development (Arsenova et al., 2015) through regular meeting and dialogue with the local peoples, including smallholders, neighbours, and local authority. All land agreement should provide fair consideration to the local land owner, transparent in the process of negotiation and legally binding.

landscape heterogeneity and reduce consumption of herbicides and pesticides through initiatives (e.g., integrated livestock farming or integrated pest management), have not been adapted in this supply chain. Landscape heterogeneity is important for the conservation of farmland biodiversity because many animal species require two or more landscape elements for their biological needs and it allows the movement of species (Azhar et al., 2015; Fahrig et al., 2011) but a more complex plantation landscape would mean less FFB yield per hectare. This is the reason why most large plantations, even one that is RSPO-certified, have extremely simple and uniform landscapes (Azhar et al., 2015). This has led to poor performance of PM1.4.1 of plantation practice.

3.3 | Sustainability improvement strategies

To close the gap and achieve sustainability in crude palm oil production from the selected supply chain, some sustainability improvement strategies are suggested in Table 3.

These improvement strategies are common ones, but their successful implementation could help close the gaps of several PMs. For example, installation of a biogas capture system would alone improve the PM for GHG emissions, increase the percentage of biomass recovery and reduce energy consumption intensity by partially substituting diesel with biogas. Secondly, improved plantation practices through agricultural intensification, such as land sparing (Devendra, 2009), could improve PMs of plantation practice, land use and species loss. Also, by engaging local smallholders and sourcing more local FFBs could improve smallholder equity, actual growth rate and to some extent improve information sharing, communication and fair partnership with the local community.

3.4 | Other recommendations

Applying the POSA framework to assess the sustainability of a crude palm oil supply chain leads to a few clear messages and recommendations:

- The data needed for the assessment are readily available throughout the supply chain. Therefore, the assessment has great potential to be accepted and adopted by the nursery, plantation owners and mill operator.
- The results calculated using site-specific data could be easily compared against the ranking criteria for PMs to identify the scores. This indicates that the ranking criteria are practical for representing actual site conditions.
- The presentation and analysis of the results showed that the sustainability gaps and hotspots could be clearly identified at different indicator levels, showing avenues for improvement within the supply chain to achieve TBL sustainability objectives.
- The POSA framework has been proven to be an evidence-informed decision-making tool for site-specific sustainability assessment for crude palm oil production. It can also potentially be used as a tool to monitor continual improvement in sustainability.

4 | CONCLUSION

The POSA framework has successfully been used to assess the most common crude palm oil production supply chain in Sarawak, Borneo, Malaysia. The selected supply chain is the most common/largest crude palm oil supply chain in Malaysia, including an MPOB-licensed oil palm nursery, and both large and smallholder plantations planted on mineral soils for FFB production for palm oil production in an oil mill with no biogas trapping facility.

The POSA framework confirms that this supply chain is not sustainable due to poor sustainability performance of some permanence measures, including smallholder equity, average annual income of workers, employment for locals, GHG emissions, percentage of biomass waste recycling and recovery at the mill, and plantation practices, known as sustainability "hotspots." The overall sustainability gap has been estimated to be −1.53. The framework has also enabled the identification of cleaner production strategies that could potentially be applied to treat the hotspots by closing the overall gap or turning gap into "0." Some of the key recommendations/strategies for the common crude palm oil supply chain include: the installation of biogas capture facilities to significantly reduce GHG emissions from POME; to improve the overall percentage of biomass waste recycling and recovery; to uphold social justice by reviewing wages for foreign plantation workers; and the sharing of economic power with the local community through smallholder development and support schemes, and local employment policies/innovative remuneration packages to increase local employment.

Thus, sustainable crude palm oil production is possible, if the authority and stakeholders in the supply chain are committed to implement the recommended cleaner production strategies through policy changes and management practices. Periodic assessment and improvement would eventually lead to sustainable crude palm oil production and bring benefits to the supply chain in the long run.

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Appendix 5 – Paper 5

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Statement of Contribution

To Whom It May Concern,

I, Chye Ing LIM, contributed to literature review, methodology development, site data collection, results analysis, discussion and writing (80%) of the paper/publication entitled:

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The remaining 20% of this paper/ publication was contributed by Wahidul K. Biswas.

Signature: Date: 31 March 2019

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Co-author 1: A/Prof Wahidul K. Biswas Date: 31 March 2019

sustainability

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Article

Sustainability Implications of the Incorporation of a Biogas Trapping System into a Conventional Crude Palm Oil Supply Chain

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Abstract: This paper presents the sustainability implications of installing biogas trapping systems in palm oil mills of a crude palm oil production supply chains in Malaysia. The study evaluates the impact of this mitigation strategy on the existing supply chains published by Lim and Biswas. The experience of a local palm oil mill installed with the KUBOTA biogas trapping system was incorporated into a typical 60 metric tonne per hour palm oil mill for effluent treatment. This allowed us to assess the changes in sustainability performance of the whole crude palm oil supply chain using the Palm Oil Sustainability Assessment (POSA) framework. Installing the biogas trapping system increased waste recycling and reuse percentage of the mill from 81.81% to 99.99% and the energy ratio (energy output/fossil fuel and biomass energy input) from 2.45 to 2.56; and reduced the Greenhouse Gas emission of the supply chain from 0.814 tonne CO_2eq to 0.196 tonne CO_2eq per tonne of Crude Palm Oil. This system could also potentially increase the mill's annual revenue by 2.3%, while sacrificing the sustainability performance of other economic indicators (i.e., a further 3% negative deviation of actual growth rate from sustainable growth rate). Overall, sustainability score of the supply chain improved from 3.47/5 to 3.59/5 on the 5-level-Likert-scale due to environmental improvement strategy consideration. Finally, this paper shows that the POSA framework is capable of capturing changes in the sustainability performance of triple bottom line indicators associated with the use or incorporation of any improvement strategy in the crude palm oil supply chain.

Keywords: palm oil; sustainability; biogas trapping; POME; cleaner production

1. Introduction

The full-fledged production of palm oil in Malaysia began in the 1980s. It has since become one of the most important sectors in the country's economic development. Whilst the industry creates job opportunities, enriches businesses (small, medium, and large), empowers local smallholders, and revives small and rural townships [1,2], it has significantly changed the country's landscape, by replacing forests and farmland with a large-scale monoculture plantation [3,4]. The lack of or absence of consultation and dialogue between producers and the local people has resulted in social conflicts [5]. Palm oil production has recently received worldwide criticism due to its increased environmental footprint at different stages of the supply chain. Apart from the 'devastating impacts' [6] on forests and species, another major environmental impact is greenhouse gas (GHG) emissions from the application of considerable amounts of synthetic fertilizer, and aerobic digestion of large volumes of palm oil mill effluent (POME) [7,8]

POME is waste water produced from the crude palm oil production process. Raw POME has low pH (4–5), a high temperature 60 °C–70 °C, a high Biochemical Oxygen Demand (BOD) of ~32,000 mg/L, a high Chemical Oxygen Demand (COD) of ~62,000 mg/L, suspended solids of 5000–54,000 mg/L, and total nitrogen of 600–1000 mg/L [9,10], compared to the acceptable limit set by the Malaysian Department of Environment (DOE). For every processed tonne of fresh fruit bunches (FFB), 0.7–1.0 m^3 of raw POME is generated [11]. Hence, a typical 60 MT/hr palm oil mill would generate about 300,000 m^3 POME waste per year, resulting an annual GHG emission of 37,000–52,000 tonnes of CO_2eq.

Madaki and Lau [12] described POME as 'the most expensive and difficult waste to manage' due to handling, storage, and treatment reasons. In order to meet the Department of Environment (DOE) water quality standards, more than 85% of palm oil mills use ponding systems (Ponding system employs biological methods, e.g., waste stabilization lagoons and oxidation (aerobic, anaerobic, facultative, maturation) ponds for wastewaters treatment. It is also used as sedimentation ponds for sludge or suspended solid settlement [13]) to treat raw POME [13,14] before it is discharged to water bodies. Whilst this ponding system is the most conventional and relatively cheaper treatment option, it has a large land footprint (about 5 hectares for a 60 MT/hr mill) and carbon footprint (i.e., 33.6 m^3 of methane per tonne of crude palm oil production through aerobic digestion) [15]. Methane is 28 times more powerful than carbon dioxide to produce global warming impact [16]. This open-space treatment also causes public nuisance as POME releases intolerable odor into the surrounding community.

To reduce the aforementioned environmental impacts associated with conventional POME treatments, the Malaysian Palm Oil Board (MPOB) has introduced new regulations that came into effect in January 2014. According to this regulation, all new palm oil mills, and existing mills that had already applied to throughput expansion, must include a 'full biogas trapping or methane avoidance facilities' [17], i.e., biogas digester (i.e., an anaerobic digestion process where methane is generated in the absence of oxygen) in the plant's design. The regulation also requires the mills that were built before January 2014 to upgrade with 'full biogas trapping or methane avoidance facilities' by 2020. Non-compliance with the regulation would risk the business losing its license to operate the mill [18]. This regulation has in fact increased the investment cost for mill owners. It is difficult to offset this incremental cost as the downstream supply chain of biogas markets is lacking [19].

Despite the resistance from stakeholders in the palm oil supply chain, the Malaysian government had introduced this new regulation to reduce the environmental impact of palm oil production. The enforcement of full biogas trapping, or methane avoidance facilities, in palm oil industries is in fact one of the eight Entry Point Projects under National Key Economic Area, with an aim to improve the sustainability performance in the palm oil sector [17].

Recent research carried out overseas showed that biogas capture from POME could deliver significant environmental benefits. Stichnothe and Schuchardt [20] carried out a life cycle assessment (LCA) to compare four types of palm oil waste management practices, including dumping Empty Fruit Bunches (EFB) and storing POME in ponding systems; using EFB in palm oil plantation and POME in ponding system; using EFB and POME for co-composting for plantation; and biogas generation from POME. The results indicated that GHG emissions from palm oil mill waste can be significantly reduced by 98% via converting methane to biogas. Besides, Nasution, et al. [21] compared open lagoon POME treatment with combinations of open lagoon technology (COLT) consisting of composting and COLT-Biogas systems in Indonesia. The study found that by replacing the open lagoon POME treatment with the COLT system could reduce GHG emissions by 357.18 kg CO_2eq. These results agree with findings in other studies [22,23], where the biogas trapping system as a POME waste treatment solution were found to significantly reduce overall GHG emissions of crude palm oil supply chains. These studies, however, mainly used life cycle assessment to estimate the GHG saving potential of biogas plants in palm oil supply chains, therefore, there exists a gap in terms of assessing other critical environmental indicators as well as economic and societal impacts. Besides, system boundaries of these studies are limited to processes during the production stage in palm oil mills, and they do not consider other stages in the entire supply chain, i.e., nursery and plantation stages.

The authors of this paper, Lim and Biswas, recently developed a POSA framework specifically for holistic sustainability assessment of crude palm oil production throughout its supply chain [24,25].

This framework was subsequently applied to assess the environmental, economic, and social sustainability implications of the most common crude palm oil supply chain of 60 MT/hr located in the Borneo Island of Malaysia [26]. They found that the overall sustainability performance of this palm oil supply chain is 1.53 points below the sustainability threshold (i.e., 3.47/5), because improvements are required in terms of GHG emissions reduction, smallholder equity enhancement, biomass waste recycling and recovery, plantation practice, as well as average wages and local employment [26]. Opportunities could exist for improving some of these indicators by complying with the government's new regulation for biogas digester installation in palm oil mills. The palm oil mill in this supply chain did not have a biogas trapping system. Thus, study's challenge was to find out the sustainability implications of incorporating a biogas trapping system into this existing crude palm oil supply chain. This allowed us to investigate the flexibility of the POSA framework in assessing changes to the supply chain when mitigation strategies are implemented.

Thus, this paper intends to evaluate:

1. The environmental, economic, and social sustainability performance of incorporating a biogas trapping system into a typical crude palm oil supply chain.
2. The level of improvement it would bring to the overall sustainability performance of crude palm oil production in Malaysia.
3. The flexibility of the POSA framework [25] in responding the changes in technology and strategies in the supply chain.

2. Methodology

This research used the POSA framework to assess sustainability implications of incorporating a biogas trapping system into the palm oil mill of a crude palm oil supply chain. A previous study conducted by the authors Lim and Biswas [26], on the most common 60MT/hr crude palm oil supply chain in Borneo Island of Malaysia, was used as a baseline for comparison. The current paper utilized raw or primary data of this 60MT/hr crude palm oil supply chain, as this research is a follow up investigation into previously published work [26].

Secondly, a KUBOTA biogas cum polishing plant (BGPP) was considered for incorporation as an improvement strategy. Accordingly, site-specific data was collected from this BGPP to investigate changes in crude palm oil supply chain sustainability performance associated with the installation of a similar BGPP in the 60 MT/hr palm oil mill. Primary data were collected from BGPP by obtaining site operational data records, interviewing stakeholders in the supply chain, and conducting surveys with local people to gather their collective feedback. Primary data were compiled and processed to determine performance measures of the environmental, economic, and social sustainability objectives of the POSA framework.

Figure 1 shows the systems boundary of a baseline crude palm oil supply chain consisting of input and output data, in order to calculate triple bottom line indicators and to show the interaction between stakeholders across this supply chain. In the comparative study, KUBOTA BGPP replaced the POME pond (Figure 2).

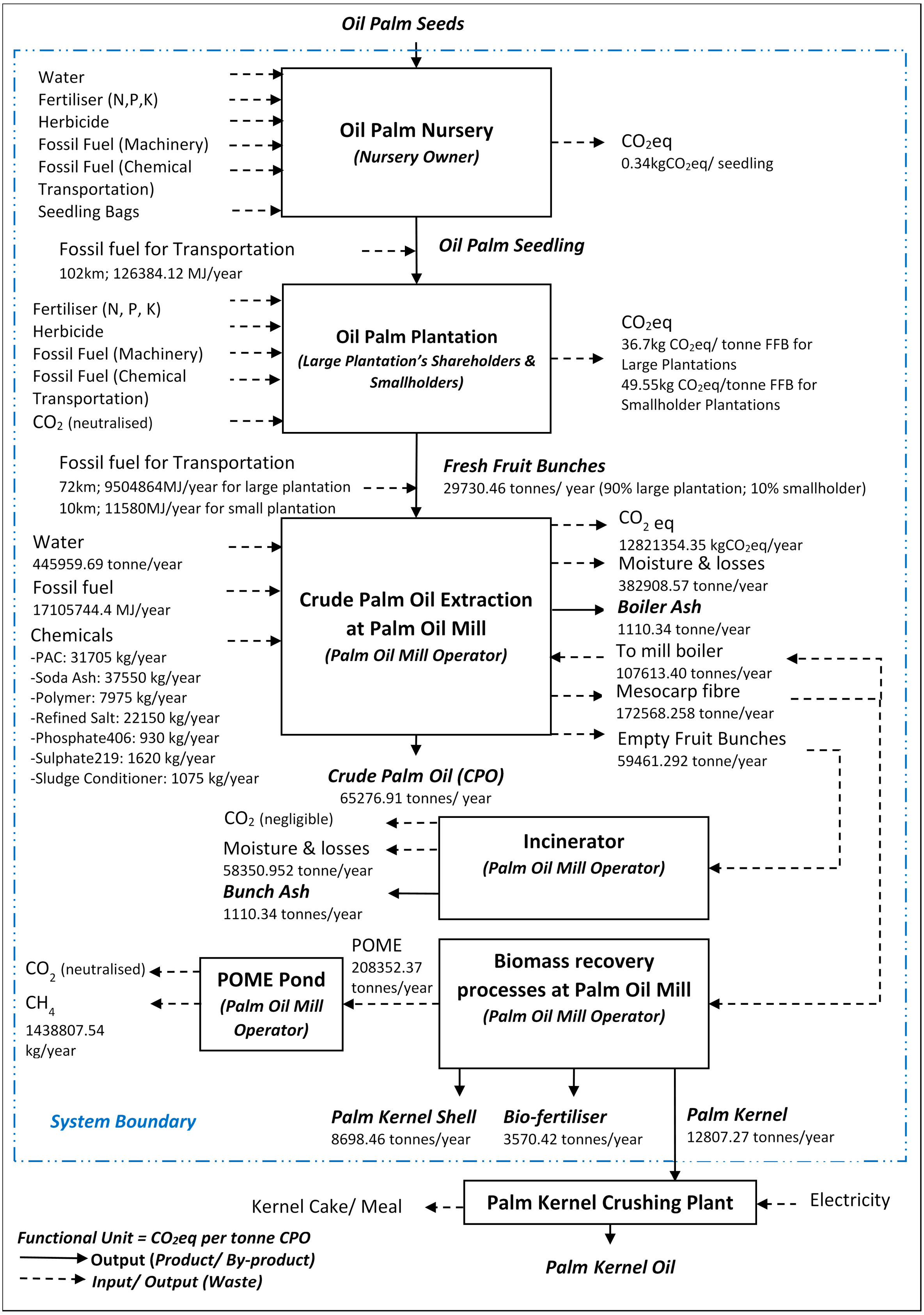

Figure 1. The reviewed baseline crude palm oil supply chain.

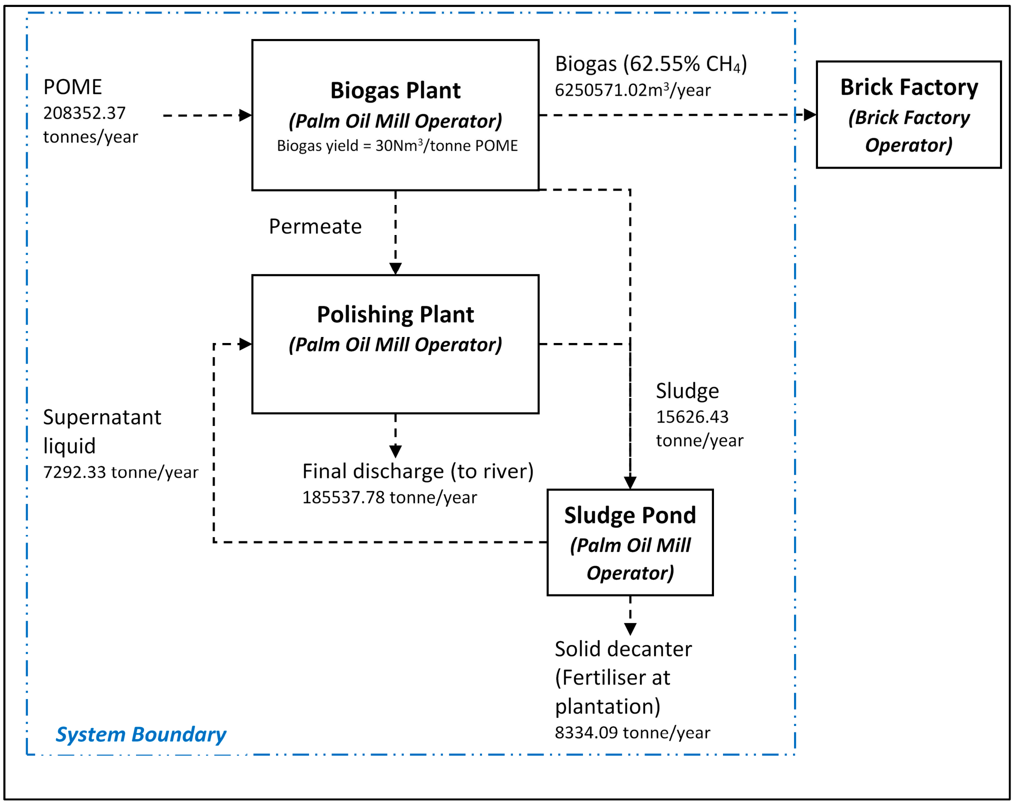

Figure 2. Kubota biogas and polishing plant (BGPP).

Thirdly, the ranking value of each Performance Measures (PM), Key Performance Indicator (KPI), Higher Performance Indicator (HPI), and overall sustainability of the supply chain with the biogas trapping system were assessed using the POSA framework [24,25,27]. Each PM was ranked on a 1–5 Likert scale, according to the pre-defined ranking criteria, where level 5 is the sustainability threshold. The sustainability gap referred to the difference between threshold value of sustainability (5) and the rank of the corresponding indicator (i.e., between 1–5), based on the quantitative site data or feedback given by the respondents in the supply chain. Each PM had a distributed weighting factor determined by the stakeholders through collective feedback on its level of importance according to Lim and Biswas [25]. The ranking value of PMs under a KPI was aggregated into the score of this KPI, and the score of KPIs under a HPI was aggregated into the score of this HPI. The overall sustainability score for the supply chain was the aggregated value of HPI scores under environment, economic, and social objectives. Lastly, the triple bottom line indicators of both crude palm oil supply chains, with and without a BGPP, were compared to assess the level of improvement in sustainability performance.

3. Review of the Baseline Crude Palm Oil Supply Chain

Inventory of the baseline crude palm oil supply chain by Lim and Biswas [26] was reviewed and revised (Figure 1). Most assumptions made in the previous study were retained except for a few, which were slightly revised to improve accuracy of the results as follows:

i. For every tonne of FFB processed, 0.7–1.0 m^3 of raw POME is generated [11]; in this study 0.8 m^3 POME per tonne FFB was used.

ii. Density of POME is 0.876 tonne/m^3 [28] (assumptions i and ii were used to calculate the amount of POME generated in this study, i.e., 0.7008 tonne of POME per tonne of FFB processed. In Lim and Biswas [26], one tonne of POME is assumed to be generated from every tonne of FFB processed, which was a less conservative estimate)

iii. Five tonnes of water are consumed for every tonne of CPO produced, and more than 50% of water consumed is discharged as POME [29,30] (assumption iii considers water loss along the palm oil mill processes, i.e., leakages, steam release, vents, etc. in addition to water discharged as POME for total water consumption. Lim and Biswas [26] did not consider this water loss throughout the milling process in calculating the water consumption)

4. The KUBOTA Biogas and Polishing Plant

The KUBOTA BGPP consisting of Anaerobic Membrane Bioreactor (AnMBR) and Polishing Plant with Membrane Bioreactor (MBR) that are considered in this case study are shown in Figures 2 and 3.

Figure 3. The biogas plant, polishing plant, the neighboring brick factory, and sludge pond in Sarawak, Malaysia (clockwise from top left corner).

The biogas plant used raw POME from palm oil mills as slurry to produce biogas at the rate of 30 Nm^3 per tonne of POME. The methane content of biogas generated from POME is 62.55% [9]. This biogas was sold to the neighboring brick factory, which is excluded from the system boundary of this study due to the fact that the biogas was regenerated from waste, and the combustion of biogas or the technology considered at a brick factory is not an outcome of the crude palm oil production process. In addition, capital equipment are usually excluded in life cycle assessment [31].

Permeate/digested slurry from the biogas plant is further treated in the polishing plant before the waste water (final discharge) is released to the river. This system was designed to achieve a BOD effluent of <20 mg/L, total nitrogen <100 mg/L, suspended solid <10 mg/L, and temperature <45 °C [10], which complies with DOE's requirements.

Digested slurry from the biogas and polishing plants is discharged to the sludge pond, where the dewatering process takes place to produce a solid decanter that could be used as fertilizer in palm oil plantations. Filtrate/supernatant liquid from the sludge ponds is returned to the polishing plant for further treatment.

The use of this biogas trapping plant with a conventional open ponding system significantly reduces the amount of land from 5 hectares to 1.5 hectares for waste management purposes [32], associated with the release of an unpleasant odor. The BGPP uses membrane processes, which require minimum maintenance such as periodic cleaning and servicing. These processes are fully automated, as it only requires a few operators that could be sourced locally.

Apart from the aforementioned field information, following technical assumptions were considered when determining PMs under the POSA framework.

i. Since the amount of sludge produced from the anaerobic process varies between 5% and 10% of treated POME [11], an average of 7.5% was considered.
ii. Solid decanter cake from the sludge pond was assumed to be 4% of POME mass [30].
iii. Density of biogas is 1.15 kg/Nm^3 [33].

5. Sustainability Implications of Incorporating a Biogas Plant

Sustainability implications of incorporating a biogas trapping system into the crude palm oil supply chain was assessed using the POSA framework. Table 1 shows the data on the sustainability performance measures of crude palm oil supply chains with and without the biogas trapping system.

Table 1. Comparing performance measures of supply chain with and without the biogas trapping system.

Sust. Obj.	Headline Performance Indicator (HPI) *		Key Performance Indicator (KPI) *		Performance Measures (PM) *		PM Values without Biogas Trapping	PM Values with Biogas Trapping
Env.	1	Natural Capital Conservation	1.1	Climate Change	1.1.1	GHG Emission (kgCO_2eq per tonne CPO)	0.814	0.196
			1.2	Air, Water and Soil Quality	1.2.1	NOx emission intensity from palm oil mill	0	0
					1.2.2	Biological Oxygen Demand of water discharged from POME pond	22.25	17
					1.2.3	Soil Nitrate Level measured through pH in waterway	92	92
			1.3	Waste Generation	1.3.1	% biomass waste recovery/recycling	81.809%	≈100%
			1.4	Biodiversity	1.4.1	Plantation Practice (Number of best practices met)	3.5/6	3.5/6
					1.4.2	Land Use	Planted on formal agricultural land	Planted on formal agricultural land
					1.4.3	Species loss	12% voted 1, 5% voted 2, 39% voted 3, 34% voted 4, 10% voted 5	12% voted 1, 5% voted 2, 39% voted 3, 34% voted 4, 10% voted 5
			1.5	Resources Consumption	1.5.1	Energy (Fossil fuel and biomass) consumption intensity (Output/Input energy ratio)	2.45	2.56
Eco.	2	Business Continuity and Resiliency	2.1	Productivity efficiency	2.1.1	Plantation yield (tonne FFB/hectare)	25.55	25.55
					2.1.2	Mill production efficiency (tonne CPO per tonne FFB)	0.2196	0.2196
			2.2	Business Continuity	2.2.1	Actual Growth Rate (deviation from sustainable growth rate)	−4%	−7%
	3	Sharing of Economic Power	3.1	Relative Poverty	3.1.1	Average annual income per worker (% of national average income)	26.95	26.95
			3.2	Local community inclusion and distribution of wealth	3.2.1	Employment opportunity for the local (% of local employment)	31.33	31.33
					3.2.2	Smallholders' equity	10%	10%

Table 1. *Cont.*

Sust. Obj.	Headline Performance Indicator (HPI) *		Key Performance Indicator (KPI) *		Performance Measures (PM) *		PM Values without Biogas Trapping	PM Values with Biogas Trapping
	4	Social Wellbeing	4.1	Meeting Essential Human Needs	4.1.1	Workers' accessibility to water supply	100%	100%
					4.1.2	Workers' accessibility to health care	100%	100%
					4.1.3	Provision of sanitation facilities to workers	100%	100%
					4.1.4	Provision of housing facilities to workers	100%	100%
	5	Social Equity	5.1	Local community empowerment and engagement	5.1.1	Sharing of information with the local community	32% voted 1, 10% voted 2, 36% voted 3, 22% voted 4, 0% voted 5	32% voted 1, 10% voted 2, 36% voted 3, 22% voted 4, 0% voted 5
					5.1.2	Fair Partnership and Community involvement in decision making	19% voted 1, 20% voted 2, 29% voted 3, 27% voted 4, 5% voted 5	19% voted 1, 20% voted 2, 29% voted 3, 27% voted 4, 5% voted 5
					5.1.3	Level of community acceptance to plantation and mill activities	85% agreement	85% agreement

* These HPIs, KPIs and PMs sourced from authors' papers on POSA framework [26]. Shaded in grey are PMs affected by the introduction of the biogas trapping system. ** It is worth mentioning that an LCA approach that follows ISO14040-44 [34,35], was only used to measure the carbon footprint/life cycle GHG emissions as the estimation of this indicator requires all upstream and downstream data.

5.1. Environmental Sustainability Performance Measures

Out of nine PMs under the environmental objectives, four PMs, i.e., PM1.1.1—GHG Emission; PM1.2.2—biological oxygen demand of water discharged from POME pond; PM 1.3.1—percentage of biomass waste recovered or recycled; and PM 1.5.2—Energy (fossil fuel and biomass) consumption intensity (output/Input energy ratio) were improved due to the incorporation of a BGPP.

PM1.1.1—GHG Emission—in the case of baseline crude palm oil supply chain without the biogas trapping system, an estimated 208,352 tonnes of POME were generated due to the production of 65,277 tonnes of CPO per year. The discharge of this POME to existing open ponding systems releases ~1439 tonnes of methane gas (i.e., 40,287 tonnes CO_2eq [16]) per year, accounting for ~76% of the supply chain GHG emissions (Table 2).

Table 2. GHG emissions from crude palm oil supply chains with and without a biogas trapping facility.

Source of Emission	GHG Emission ($kgCO_2eq$)			
	Without Biogas Trapping		*With Biogas Trapping*	
Smallholder FFB	1.47×10^6	2.77%	1.47×10^6	11.48%
Large Plantation FFB	9.82×10^6	18.49%	9.82×10^6	76.55%
Water	1.23×10^2	0.00%	1.23×10^2	0.00%
Fossil Fuel consumed by mill	1.50×10^6	2.83%	1.50×10^6	11.73%
Methane from POME	4.03×10^7	75.86%	*N/A*	*N/A*
Chemical for Water Treatment Plant	2.45×10^4	0.05%	2.45×10^4	0.19%
Chemical for biogas/polishing plant	*N/A*	*N/A*	6.21×10^3	0.05%
Total	$\mathbf{5.31 \times 10^7}$	**100.00%**	$\mathbf{1.28 \times 10^7}$	**100.00%**

FFB production was the second largest emitter of GHG after POME. It was found that large plantations that contribute to 90% equity emitted less GHG for FFB production (i.e., 36.7 $kgCO_2$eq) than the smallholders' plantations that contributed to 10% of the equity in the supply chain (i.e., 49.55 $kgCO_2$eq), due to the use of efficient machinery, and fertilizer management practices [36]. In addition, large plantations have skilled manpower and management systems to optimize its operation. This research estimated that the incorporation of a BGPP into the palm oil mill of supply chains could significantly reduce GHG emissions by 75.9% mainly due to the complete elimination of methane from POME. There was, however, a release of negligible amounts of GHG (i.e., 0.05% of total emission) from this plant due to the use of chemicals in membrane cleaning processes in BGPP.

PM1.2.2—biological oxygen demand of water discharged from POME ponds—the POME treatment, using conventional ponding system, in the current analysis met the DOE's requirement for BOD of waste water discharge <100 mg/L. This was because the BGPP system could further reduce the BOD to a level below 20 mg/L. However, the use of this open ponding system during the time of flood is risky, as POME could overflow and pollute fresh water in surrounding areas. Since POME is enclosed in the biogas trapping plant, it eliminates the risks associated with water and ground pollution in the event of a flood.

PM 1.3.1—percentage of biomass waste recovered or recycled—biomass waste generated from the mill is equal to the mass of FFB minus the mass of main products, i.e., crude palm oil and palm kernel. Biomass waste, in the form of EFB and mesocarp fiber, contains useful materials and energy that could be recovered. The recovery processes in the existing system of palm oil mill use most of these biomass wastes (82%) for palm kernel shell, bio-fertilizer production, and energy generation. Part of this biomass waste is used as fuel in the boiler to generate steam for the milling process. The ash generated due to combustion of this waste for energy generation was purchased by the neighboring cement factory for its use as a partial replacement of cement in concrete [37]. This ash was also used as a substitute for potassium organic fertilizer [38]. The rate of recovery or recycling of biomass waste (i.e., PM 1.3.1) could increase due to the introduction of this biogas trapping system.

Of the biomass waste (i.e., 39,878 tonnes per year) generated from the palm oil mill in the existing supply chain, 18% is unrecoverable and is discharged in the form of POME. The installation of a biogas trapping plant in the system converts this unused biomass waste that exists in POME into methane for energy generation. Figure 4 shows that the biomass waste recovery in palm oil mills increased from 82% to 99.99% due to the use of the biogas trapping system. Only a small portion of biomass waste was unrecovered in this new system, which is the suspended solid in the final discharge/effluent (i.e., about 0.001% of the final discharge, <10 mg/L).

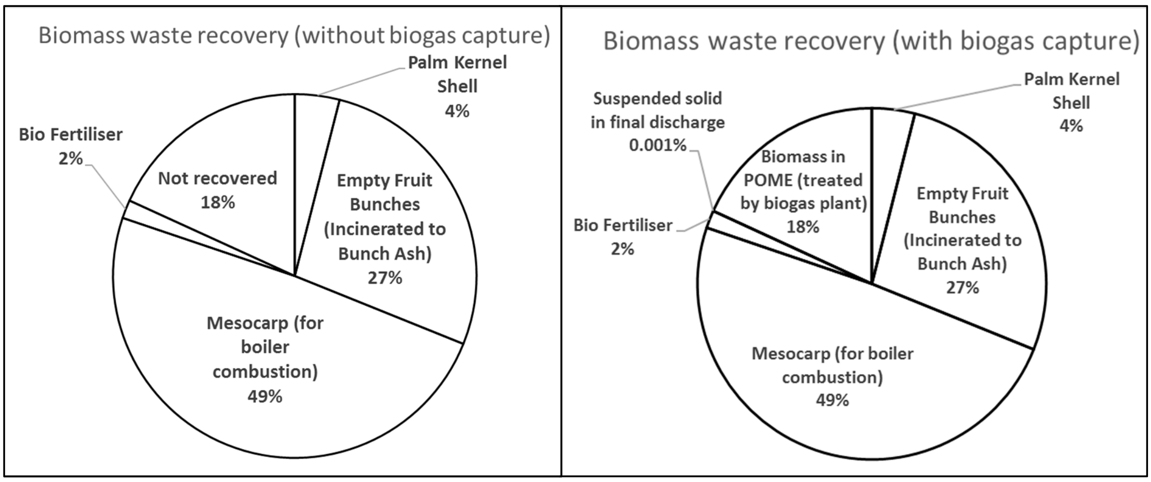

Figure 4. Biomass waste recovery in the palm oil mill (with and without the biogas trapping system).

Biogas generated from the KUBOTA BGPP was used by the neighboring brick factory and formed an industrial symbiotic relationship. This biogas could alternatively be used in situ to supplement the energy needed at the mill's steam boiler and reduce demand for mesocarp fiber. This saved mesocarp fiber could then either be sold as a fuel to other industries or be further processed into fertilizer. This is because the transportation of mesocarp fiber by trucks could be more convenient than delivering gas through a complex pipe network to meet the energy demands of downstream customers in isolated locations, where these palm oil mills are located.

PM 1.5.2—energy (fossil fuel and biomass) consumption intensity (output/input energy ratio)—the biogas trapping system traps 3,909,732 m^3 methane gas per year for a 60 MT/hr mill, which is equivalent to 145 TJ of energy. This increases the total energy output from the crude palm oil supply chain by 4.6%. Therefore, PM 1.5.2, which is measured in terms of output/input energy ratio increased from 2.45 to 2.56. Although the energy output/input ratio is low (rank at level 1/5), it is worth noting that 96.9% of the energy input to the supply chain that mainly generates steam in the milling process, comes from biomass waste recovered from the supply chain. This conserves 7233 tonnes equivalent of coal (assuming coal heating value of 20 MJ/kg) for the future generation and thereby, enhances intergenerational social equity. Fossil fuel consumption for machinery at nurseries and plantations, for transportation and diesel generators at palm oil mills amounted to 3.1% of the total energy input of the supply chain. In this case, fossil fuel consumption remained unchanged with the introduction of BGPP, as the biogas produced was considered to be sold to the neighbor brick factory through an industrial symbiotic process.

5.2. Economic Sustainability Performance Measures

BGPP instillation requires a capital investment of USD 2.9 million (RM11.6 million) and an operational expenditure of USD 0.12 million (RM 0.48 million) per year, for an investment period of 16 years [39]. Biogas supply to the neighboring plant could increase the mill's annual revenue by RM 4.52 million (consider RM 33 per MMBtu [40]) by selling this to the neighboring brick factory. Hence, the profit was estimated to be RM 4.04 million per year with a payback period of 2.87 years (Assuming 1USD = RM4).

PM2.2.1—deviation of actual growth rate (AGR) from sustainability growth rate (SGR) evaluates if the palm oil mill's growth is healthy for long term business continuity and resiliency. Growing too fast (i.e., a positive deviation) or too slow (i.e., a negative deviation) are both not economically sustainable for the business [41,42]. A positive deviation of AGR from SGR means that the business cannot be sustained without additional borrowing, and a negative deviation means the business is underperforming considering the assets and cash it has in hand.

The additional investment on this environmental mitigation strategy increased the profit and revenue but also increased the value of assets and debts. Table 3 compares the financial status of the palm oil mill before and after one year of BGPP investment. The introduction of BGPP increased the sustainable growth rate of the palm oil mill, i.e., the maximum growth rate that the mill can sustain without having to increase financial leverage from 10% to 16% due to the higher return on equity and business retention rate. AGR of the palm oil mill increased from 6% to 9% due to the higher recent sale figures, with additional revenue generated from selling the biogas. An increase in growth due to the introduction of BGPP seems to have a positive impact on the supply chain, but it leads to a larger deviation of actual growth rate from sustainable growth rate of −4% to −7%, hence causing a negative economic impact to PM 2.2.1.

This deviation could be narrowed by reducing SGR through the productive use of excess cash, e.g., increasing dividends of shareholders or reducing business debt levels [42]. Alternatively, AGR can be increased by increasing sales, through processing more FFB into CPO, palm kernel, and other by-products with existing facilities.

Table 3. Comparing financial status before and after BGPP investment.

ID	Description	Formula	Unit	Without BGPP	With BGPP
a.	Sales figure from starting point		RM	11,547,410	11,547,410
b.	Most recent sales figure		RM	12,199,346	12,576,410
c.	Total Sales throughout the year		RM	177,959,338	182,484,110
d.	Total Assets at year end		RM	70,737,661	82,337,661
e.	Dividend		RM	4,282,930	5,569,167
f.	Net Income		RM	9,392,273.	13,437,045
g.	Total Debt at year end		RM	40,123,436	51,723,436
h.	Total Assets at year end		RM	70,737,661	82,337,661
i.	Asset Utilization Rate	c/d	%	252%	222%
j.	Profitability Rate	f/c	%	5%	7%
k.	Financial Utilization Rate	g/l	%	131%	169%
l.	Total Equity	h - g	RM	30,614,225	30,614,225
m.	Return on Equity	I* j* k		0.17	0.28
n.	Dividend Rate	e/f	%	45.60%	41.45%
o.	Business Retention Rate	1 - n	%	54.40%	58.55%
p.	Sustainable Growth Rate	m * o	%	10%	16%
q.	Actual Growth Rate	(b - a)/a	%	6%	9%
r.	Actual Growth Rate deviation from Sustainable Growth Rate	q - p	%	−4%	−7%

Figures 5–7 illustrate the sensitiveness of total debt reductions, increased dividend, and increased production (hence increase sales and net income) to SGR, AGR, and the deviation of AGR from SGR. AGR will remain constant, and SGR will be reduced if the total debts are cut down. The calculation shows that reducing total debts up to 23% of current debt levels would bring down the deviation of AGR from SGR to zero provided all other parameters (e.g., dividend) remain the same. SGR will also be reduced with smaller impact, if the dividend paid to shareholders is increased (Figure 6). A more effective way to reduce the difference between AGR and SGR, is by increasing sales and net income through increased production. Figure 7 shows that increasing both sales and net income by 9% would reduce the difference between AGR and SGR to zero.

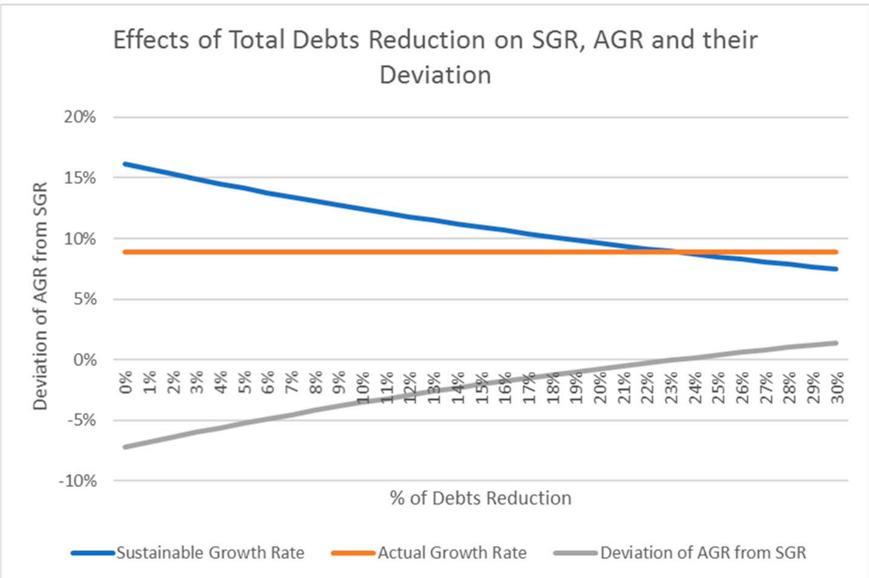

Figure 5. Effects of total debts reduction on SGR, AGR, and their deviation.

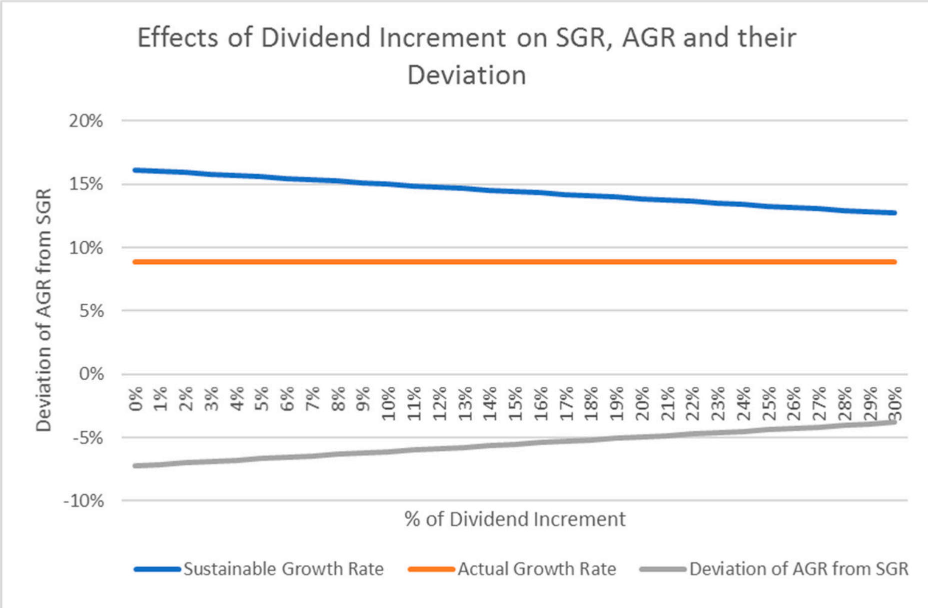

Figure 6. Effects of dividend increment on SGR, AGR, and their deviation.

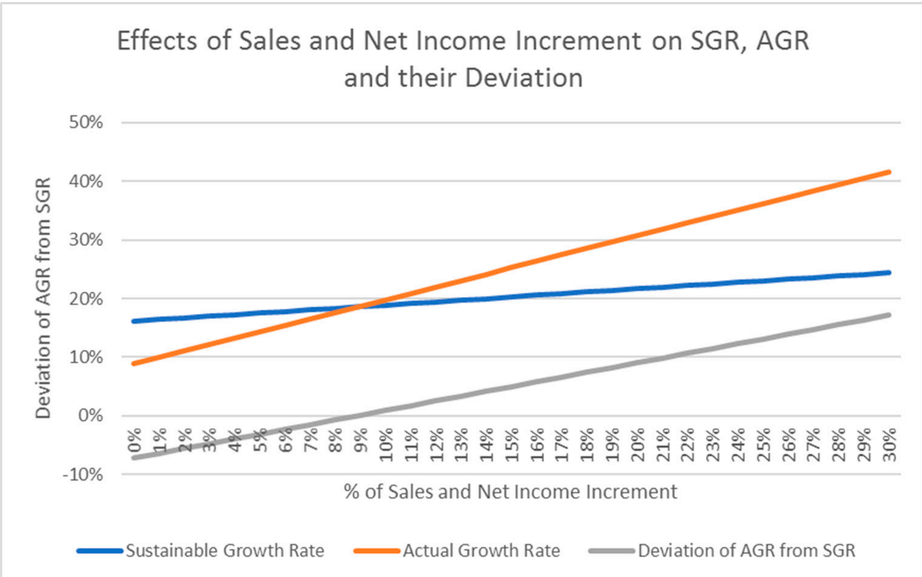

Figure 7. Effects of sales and net income increments on SGR, AGR, and their deviation.

The economic PMs including PM2.1.1—plantation yield (tonne FFB/hectare); and PM2.1.2—mill production efficiency (tonne CPO per tonne FFB), do not seem to be affected by the introduction of a biogas trapping system. This is because the BGPP only processes POME waste and does not affect plantation activities and other crude palm oil extraction processes at the palm oil mill. The revenue, profit, and cash flow have increased, but this extra earning neither directly benefitted the workers nor the local community, probably due to consideration of other higher priority areas such as debts reduction as the business had increased the capital investment through extra bank financing. Hence, PM3.1.1, i.e., average annual income per worker, which is the percentage of national average income, and PM3.2.2 (i.e., smallholders' equity) remain unchanged. The BGPP requires minimum human involvement during operation while the periodic maintenance task could be performed by the existing manpower in the palm oil mill. Hence, the number of job opportunities for the local people (i.e., PM3.2.1 or employment opportunity for the locals) remains the same.

5.3. Social Sustainability Performance Measures

Table 1 shows that the introduction of a biogas trapping system does not have an immediate and direct effect on the social sustainability performance measures. In both supply chain scenarios, with and without a biogas trapping system, the HPI of social wellbeing was achieved by fulfilling the essential needs, including water supply, healthcare, sanitation facilities, and housing facilities for workers (PM 4.1.1–4.1.4). The supply chain practiced the same administrative strategies on workers' welfare, regardless of whether a biogas trapping system is installed or not.

HPI of social equity (i.e., local community empowerment and engagement), which is attained by sharing information with the local community (PM5.1.1) and by offering fair partnership and community involvement in decision making (PM5.1.2), were not impacted by the biogas trapping system. This is because the incorporation of the BGPP does not affect the local community in terms of land accusation, pollution creation, and businesses, and so the consultation was not deemed necessary. This was mainly driven by governing policies but not by community pressure.

This new development can potentially improve the level of community acceptance to plantation and mill activities (PM 5.1.3), as the conversion of POME to biogas can reduce the unpleasant odor produced by the open POME pond. It should be notable that the Department of Environment in Malaysia receives ~1,082 complaints each year about odor pollution and this accounts for 2.4% of the cases lodged/filed each year, and is ranked sixth as the major sources of odor pollution in the country [43]. However, improvements on the level of community acceptance cannot be observed immediately as it takes time for stakeholders to observe the system's implications.

5.4. The Overall Sustainability Assessment

Sustainability assessment results of crude palm oil supply chains, with and without a biogas trapping system, were determined using the POSA framework. Ranks of PMs were determined by comparing the data of PMs against the ranking criteria, while scores for KPIs, HPIs, sustainability objectives, and overall sustainability were calculated using formulae developed by Lim and Biswas [25]. For comparison purposes, rank value of PMs and score for KPIs, HPIs, sustainability objectives, and overall sustainability of the existing supply chain (i.e., without a biogas trapping system) were included in italic within brackets (Table 4).

The overall sustainability score improved from 3.47 to 3.59 out of 5, due to the incorporation of a biogas trapping system. Most of the improvements took place from an environmental perspective. The HPI score of Natural Capital Conservation in the baseline supply chain increased from 2.94 out of 5 to 3.54 out of 5 due to this improvement strategy. KPI 1.1—climate change—was significantly improved due to higher performance of its PM 1.1.1—GHG emissions (76% reduction in GHG emission). This had in fact reduced the gap between the rank and the sustainability threshold of this PM from 3 to 1. Similarly, the gap for KPI 1.3—waste generation was reduced from 1 to 0 by improving the recovery of biomass waste by 17% (i.e., PM 1.3.1—percentage of biomass waste recovered/recycled).

The incorporation of biogas plant in the supply chain was found to increase the deviation of actual growth rate from sustainability growth rate by −3%, hence the ranking of its PM 2.2.1—actual growth rate—dropped from 4 out of 5 to 3 out of 5. This has been reflected on the score for KPI 2.2—business continuity—HPI 2 of business continuity, and resiliency of the overall economic sustainability objective.

There were no changes in the scores of PMs, KPIs, HPIs, and sustainability for social sustainability objectives. This means that the incorporation of a biogas plant in the supply chain does not cause social consequences.

Table 4. Sustainability assessment of crude palm oil supply chain with biogas trapping using POSA framework.

Sust. Obj.	Headline Performance Indicator		Key Performance Indicator		Performance Measures		Ranking for PM	Overall Weight for PM	Score for KPI	Score for HPI	Score for Sust. Obj.	Score for Overall Sust.
Env.	1	Natural Capital Conservation	1.1	Climate Change	1.1.1	GHG Emission	**4** *(2)*	**0.045**	**4.00** *(2.00)*	**3.54** *(2.94)*	**3.54** *(2.94)*	**3.59** *(3.47)*
			1.2	Air, Water and Soil Quality	1.2.1	NOx emission intensity from palm oil mill	**5** *(5)*	**0.0393**	**5.00** *(5.00)*			
					1.2.2	Biological Oxygen Demand of water discharged from POME pond	**5** *(5)*	**0.0447**				
					1.2.3	Soil Nitrate Level measured through pH in waterway	**5** *(5)*	**0.0444**				
			1.3	Waste Generation	1.3.1	% Biomass waste recovery/recycling	**5** *(4)*	**0.045**	**5.00** *(4.00)*			
			1.4	Biodiversity	1.4.1	Plantation Practice	**2** *(2)*	**0.0463**	**2.68** *(2.68)*			
					1.4.2	Land Use	**3** *(3)*	**0.0447**				
					1.4.3	Species loss	**3** *(3)*	**0.0538**				
			1.5	Resources Consumption	1.5.1	Energy (Fossil fuel and biomass) consumption intensity (Output/Input energy ratio)	**1** *(1)*	**0.0415**	**1.00** *(1.00)*			
Eco.	2	Business Continuity and Resiliency	2.1	Productivity efficiency	2.1.1	Plantation yield	**5** *(5)*	**0.0476**	**5.00** *(5.00)*	**4.00** *(4.50)*	**2.88** *(3.13)*	
					2.1.2	Mill production efficiency	**5** *(5)*	**0.0485**				
			2.2	Business Continuity	2.2.1	Actual Growth Rate	**3** *(4)*	**0.0447**	**3.00** *(4.00)*			
	3	Sharing of Economic Power	3.1	Relative Poverty	3.1.1	Average annual income per worker	**2** *(2)*	**0.0452**	**2.00** *(2.00)*	**1.76** *(1.76)*		
			3.2	Local community inclusion and distribution of wealth	3.2.1	Employment opportunity for the local	**2** *(2)*	**0.0471**	**1.52** *(1.52)*			
					3.2.2	Smallholders' equity	**1** *(1)*	**0.0439**				
Soc.	4	Social Wellbeing	4.1	Meeting Essential Human Needs	4.1.1	Workers' accessibility to water supply	**5** *(5)*	**0.0471**	**5.00** *(5.00)*	**5.00** *(5.00)*	**4.34** *(4.34)*	
					4.1.2	Workers' accessibility to health care	**5** *(5)*	**0.0476**				
					4.1.3	Provision of sanitation facilities to workers	**5** *(5)*	**0.0474**				
					4.1.4	Provision of housing facilities to workers	**5** *(5)*	**0.046**				
	5	Social Equity	5.1	Local community empowerment And engagement	5.1.1	Sharing of information with the local community	**3** *(3)*	**0.0425**	**3.68** *(3.68)*	**3.68** *(3.68)*		
					5.1.2	Fair Partnership and Community involvement in decision making	**3** *(3)*	**0.0433**				
					5.1.3	Level of community acceptance to plantation and mill activities	**5** *(5)*	**0.0444**				

With the implementation of a biogas trapping system, hotspot of the crude palm oil supply chain in PM 1.1.1—GHG emission—could potentially be eliminated. Other hotspots (i.e., PM 1.4.1—plantation practice; PM1.5.2—energy (fossil fuel and biomass) consumption intensity (output/input energy ratio); PM3.1.1—average annual income per worker; PM3.2.1—employment opportunity for the local; and PM 3.2.2—smallholders' equity) would not likely to be improved. Thus, some new strategies could be considered in the future, such as integrated livestock farming, pesticide and herbicide management, local skill development, and smallholder's support program for reducing economic and environmental hotspots (list few within this bracket in short) and to further reduce the overall sustainability gap.

6. Discussion

Our results show that implementing a biogas trapping system to the most common crude palm oil supply chain in Malaysia allows the supply chain to reduce the sustainability gap. The results of this assessment, using the POSA framework, are consistent with findings of others in the literature [20–23], where GHG emissions were significantly reduced with the introduction of a biogas plant. This assessment also found improvements in other environmental sustainability indicators, including biological oxygen demand of the water discharged, percentage biomass waste recovery/recycling, and energy (fossil fuel and biomass) consumption intensity (output/input energy ratio). The land size required for waste treatment could also be reduced from 5 hectares to 1.5 hectares (70% reduction). This reduction in land size, however, is insignificant in making an impact as the land used for plantation, which is reflected in PM 2.1.1 plantation yield (in tonne FFB per Ha) is much larger compared to this saving. The results show that the biogas trapping system could cause beneficial repercussions in terms of enhanced environmental sustainability performances. Whilst overall environmental sustainability performance improved due to this biogas trapping plant, some other specific environmental impacts that depend on plant management system, such as plantation practice, land use, and species loss are still substantial and did not reach the sustainability threshold. This confirms that the sustainability policy, along with technological improvements are required to achieve significant sustainability improvements in the supply chain.

PM1.5.1—energy (fossil fuel and biomass) consumption intensity (output/input energy ratio) remains the hotspot despite the fact that the biogas plant contributes to additional energy output to the supply chain. While strategies and efforts should be involved in order to reduce fossil fuel consumption during plantation, milling, and transportation stages, it is worth reviewing the definition of the energy input in calculating this PM. The current calculation method includes energy input obtained from the biomass waste generated within the system boundary. It could have been more accurate to consider the net energy input in the system boundary of the supply chain [44,45], which could have also highlighted the importance of energy conservation and recovery within the supply chain.

The installation of a biogas trapping system can increase the revenue and net profits of the palm oil mill of the baseline supply chain. The additional investment is economically feasible as a breakeven point can be attained in less than 3 years. The additional capital investment due to incorporation of this biogas trapping system can cause debts, and as the mill was underutilized, it could lead to a significant deviation of actual growth rate from sustainable growth rate. With current facilities' capacity and investment, the supply chain could have produced more crude palm oil and palm kernel for sustainable growth. The shortage of FFB supply due to labor shortage and lower CPO market price, are some main key possible barriers to increase the growth of sales [46,47].

The introduction of a biogas trapping system does not play a role to combat poverty and wealth creation, meaning that it does not help increase average annual income per worker, create employment opportunity for the local people, and increase smallholders' equity in this case study. However, with the increase of revenue and profit, the supply chain has greater financial ability to improve the welfare of its employees. Palm oil mill owners in the supply chain could introduce schemes such as the employee stock options plan [48] to improve the social security of their employees, which would reward, retain, and attract local employees. Employee stock options plan offers company shares to the employees and thus the employees could own part of the company. They could also benefit directly through the annual dividend when the company is making a profit. Making the employees shareholders of the company meets the economic sustainability objective of sharing economic power through distribution of wealth.

The biogas trapping system does not make any changes to the social sustainability performance. The perception and level of acceptance of the local community towards the palm oil supply chain is expected to be more positive by reducing key environmental impacts, and also by eliminating odor nuisance/pollution.

While the biogas trapping system helps improve the overall sustainability performance of the crude palm oil supply chain, it cannot totally close the sustainability gap. Other environmental sustainability issues need to be resolved in terms of further reduction of fossil fuel consumption, improved plantation practice to reduce the loss of biodiversity, and land usage, initiatives for species protection, and by further reducing GHG emissions to meet the international target (i.e., 0.15 tonne CO_2eq/tonne CPO, considering Malaysia's pledge in Copenhagen for a 40% reduction in GHG emission by 2020 from 2005 level). This holistic framework also demonstrates that there exists large economic and social sustainability gaps, particularly in sharing economic power and uplifting social equity, which remain major areas of improvement, despite the efforts that could be made by installing the biogas trapping system. These economic and social sustainability indicators would require new administrative strategies and policy changes along the supply chain, e.g., increasing the share of fresh fruit bunches collected from smallholders, and the practice of community-inclusive policy in decision making, to make significant improvements.

The incorporation of technological changes in the supply chain modified the system boundary but it did not affect the sustainability assessment process using the POSA framework. The quantifiable framework thus demonstrates flexibilities or captures any sort of changes associated with the incorporation of strategies in the crude palm oil supply chain to enhance the sustainability performance. Key characteristics of the POSA framework that are generated from this research are its comprehensiveness, decision making capability, and holistic or multidisciplinary assessment by examining all indicators of the three sustainability objectives.

7. Conclusions

The paper demonstrates the flexibility of POSA framework to incorporate any improvements into the existing supply chain of crude palm oil production for sustainability assessment. The incorporation of a biogas trapping system in palm oil mills for POME treatments as an environmental improvement strategy, has improved the overall sustainability performance score of a typical crude palm oil production supply chain in Malaysia from 3.47 out of 5 to 3.59 out of 5. This POSA framework captured the changes/side effects associated with the incorporation of a biogas trapping system into the supply chain. Environmental indicators such as GHG emissions, BOD, and waste recovery were improved due to inclusion/consideration of this environmental improvement strategy but the performance of actual growth rate decreased.

There still exists a significant gap to achieve a complete sustainability outcome (i.e., 5 out of 5), as the incorporation of one improvement strategy is not enough. This research using the POSA framework has further identified that biodiversity, wealth distribution, and social equity are some areas that require a significant level of improvement using relevant improvement strategies to close this gap. The biogas trapping system would solve part of the problem but achieving sustainability production of crude palm oil remains a challenge to all stakeholders in the supply chain.

Similarly, other strategies can be incorporated into or trialed in the POSA framework until the sustainability performance gap becomes very close or equal to zero. This way the framework could enable policy makers, businesses, and customers in the supply chain to discern right strategies in attaining sustainable crude oil production in Malaysia.

This framework is limited to the crude palm oil production, but the system boundary could be further extended by incorporating the refinery production processes to generate a finished product, e.g., olein for cooking oil and biodiesel, stearin for margarine and shortening. Besides, the accuracy in estimating some performance measures could be improved, e.g., species loss could be measured using scientific methods (e.g., the species–area curve [49]) rather than collective feedback, soil nitrate levels could be measured directly with a flow injection analyzer [50] rather than through pH in water way.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

AGR	Actual Growth Rate
BGPP	Biogas cum Polishing Plant
BOD	Biochemical Oxygen Demand
CO_2eq	Carbon Dioxide Equivalent
COD	Chemical Oxygen Demand
CPO	Crude Palm Oil
DOE	Department of Environment
EFB	Empty Fruit Bunches
FFB	Fresh Fruit Bunches
GHG	Greenhouse Gas
HPI	Higher Performance Indicator
KPI	Key Performance Indicator
m^3	cubic meter
mg/L	Milligram per litre
MJ	Mega joule
MT/hr	Metric tonne per hour
Nm^3	Normal Cubic Meter
PM	Performance Measure
POME	Palm Oil Mill Effluent
POSA	Palm Oil Sustainability Assessment
SGR	Sustainable Growth Rate

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Appendix 6 – Patent Registration

Lim, Chye Ing, and K. Biswas Wahidul. 2017. Palm Oil Sustainability Assessment (POSA) Framework. edited by Intellectual Property Corporation of Malaysia. Malaysia.

Patents Form No.1 PATENTS ACT 1983 REQUEST FOR GRANT OF PATENT (Regulations 7(1)) To: The Registrar of Patents Patents Registration Office Kuala Lumpur, Malaysia	For Official Use APPLICATION NO: **PI 2017704083** Filing Date: **27/10/2017** Fee received on: **27/10/2017** Amount: **RM330**
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II. APPLICANT(S) (the data concerning each applicant must appear in this box or , if the space insufficient, in the space below):

Name: **CURTIN (MALAYSIA) SDN BHD**
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Additional Infomation (if any)

III.INVENTOR:

Applicant is the inventor: Yes No √
If the applicant is not the inventor
Name: **Lim Chye Ing**
Address: **Lot 7445, Greenville, Jalan Promin Jaya 1, Senadin 98100 Miri SARAWAK MALAYSIA**

Applicant is the inventor: Yes No √
If the applicant is not the inventor
Name: **Wahidul K. Biswas**
Address: **Curtin University 6845 AUSTRALIA**

A statement justifying the applicant's to the patent accompanies this Form

Yes √ **No**

Additional Information (if any)

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Agent Registration No:
Applicant has appointed to be their representative: **---**

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This application is a divisional application
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Date of disclosure:

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If not yet allocated, please tick
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Web research.curtin.edu.au

02-Sep-2016

Name: Wahidul Biswas
Department/School: Sustainable Engineering Group
Email: W.Biswas@curtin.edu.au

Dear Wahidul Biswas

RE: Ethics approval
Approval number: HRE2016-0267

Thank you for submitting your application to the Human Research Ethics Office for the project **Sustainability assessment of Malaysian Palm Oil Industries**.

Your application was reviewed through the Curtin University low risk ethics review process.

The review outcome is: **Approved**.

Your proposal meets the requirements described in National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research (2007).*

Approval is granted for a period of one year from **02-Sep-2016** to **01-Sep-2017**. Continuation of approval will be granted on an annual basis following submission of an annual report.

Personnel authorised to work on this project:

Name	Role
Biswas, Wahidul	CI
Lim, Chye Ing	Student

Standard conditions of approval

1. Research must be conducted according to the approved proposal
2. Report in a timely manner anything that might warrant review of ethical approval of the project including:
    - proposed changes to the approved proposal or conduct of the study
    - unanticipated problems that might affect continued ethical acceptability of the project
    - major deviations from the approved proposal and/or regulatory guidelines
    - serious adverse events

3. Amendments to the proposal must be approved by the Human Research Ethics Office before they are implemented (except where an amendment is undertaken to eliminate an immediate risk to participants)
4. An annual progress report must be submitted to the Human Research Ethics Office on or before the anniversary of approval and a completion report submitted on completion of the project
5. Personnel working on this project must be adequately qualified by education, training and experience for their role, or supervised
6. Personnel must disclose any actual or potential conflicts of interest, including any financial or other interest or affiliation, that bears on this project
7. Changes to personnel working on this project must be reported to the Human Research Ethics Office
8. Data and primary materials must be retained and stored in accordance with the Western Australian University Sector Disposal Authority (WAUSDA) and the Curtin University Research Data and Primary Materials policy
9. Where practicable, results of the research should be made available to the research participants in a timely and clear manner
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11. Ethics approval is dependent upon ongoing compliance of the research with the Australian Code for the Responsible Conduct of Research, the National Statement on Ethical Conduct in Human Research, applicable legal requirements, and with Curtin University policies, procedures and governance requirements
12. The Human Research Ethics Office may conduct audits on a portion of approved projects.

Special Conditions of Approval

None.

This letter constitutes ethical approval only. This project may not proceed until you have met all of the Curtin University research governance requirements.

Should you have any queries regarding consideration of your project, please contact the Ethics Support Officer for your faculty or the Ethics Office at hrec@curtin.edu.au or on 9266 2784.

Yours sincerely

Dr Catherine Gangell
Manager, Research Integrity

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> Dear sir,
>
>
> I am preparing my PhD thesis by publication and would like to request
> for your permission to use papers that I published in your journal of
> "Sustainability" in the thesis.
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>
> Attached is a letter containing details of my request. Kindly revert
> the reply slip to me.
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> Your kind permission is highly appreciated.
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>
> Regards,
>
> Chye Ing LIM

>

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