INTEGRATED SUSTAINABILITY ASSESSMENT FRAMEWORK WITH MITIGATION STRATEGY FOR PALM OIL MILL

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DEDICATION

This thesis is dedicated to my father and mother, Jamaludin and Haziatul, this is for you the one who keep giving endless support since day one until today, for working hard to give me the best education and providing me with the time and resources to pursue my dreams. A special feeling of gratitude to my siblings, Nadiah, Nabil, Naufil, Naquib and Nazheef for being there for me throughout the entire doctorate program. All of you have been my best cheerleaders. To my beloved grandpa and grandma, I can’t thank you enough for all of your thoughts and prayers all this time. To my husband, Muhd Fairis thank you for constantly being by my side, who was always there to lend a helping hand, for being my best friend and critique – I am very thankful. Alhamdulillah.

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ABSTRACT

Over the past decades, palm oil mills have been proven to be a profit-making industry. The rapid advancement of this industry poses many challenges from non-government organisations and society to ensure that the operation and production of the palm oil mills remain sustainable. Therefore, many palm oil industries are now committing to adhere to certification schemes to further improve their mill management towards sustainability and reduced greenhouse gas (GHG) emissions. However, the current palm oil certification scheme has several drawbacks and limitations that burden the industry. This study presents the development of an integrated palm oil mill carbon footprint and accounting (POMCFA) and a novel palm oil mill sustainability index (POMSI) framework that incorporates mitigation strategy selection tool. This framework enables millers to assess the carbon footprint and sustainability performance of their palm oil mills using one palm oil mill inventory. First, this study developed the POMCFA parameters and indicators to calculate the carbon emissions of the mill. This measurement was based on the carbon dioxide equivalent (CO2e). The parameters and indicators of POMCFA were then included as part of the POMSI database. Following that, the POMSI assessment was performed via the adoption of a proximity-to-target approach that measures the current sustainability performance of an industry relative to the policy targets. The POMCFA performance was obtained in terms of total CO2e and GHG profile. The POMSI performances were then translated into five rating systems to describe the sustainability performance levels of the industries i.e. excellent, good, fair, poor, and very poor. An industry-comparable performance was observed using a graphical method. Selected palm oil mills in Malaysia were used as case studies to demonstrate the applicability of the framework. Based on the result, it was found that several indicators of POMCFA and POMSI did not perform efficiently. By identifying the weak-performing indicators, profound recommendations for integrated improvement measures were proposed. In particular, a mitigation selection tool was developed to select the technology to improve upon the weaknesses in the model. Then, the POMCFA and POMSI scores were recalculated to evaluate the effectiveness of the proposed strategy on the sustainability performance and/or CO2e emission of the mill. This method enables the industry to continuously measure and keep track of emissions performance and sustainability practices. The assessments give the impetus for every mill to compete towards better improvement and to learn from each other, besides working to improve industry performance as a whole. In addition, the comprehensive assessment offered by the mitigation model in this study results in a better analysis; in turn, helping the relevant industries in making decisions to continuously improve performance with optimal decision solutions.

ABSTRAK

Sejak beberapa dekad yang lalu, kilang kelapa sawit telah dibuktikan sebagai suatu industri yang menguntungkan. Kemajuan pesat industri ini telah menimbulkan banyak kritikan daripada organisasi bukan kerajaan dan masyarakat untuk memastikan operasi dan pengeluaran kilang kelapa sawit kekal mampan. Oleh itu, banyak industri minyak sawit kini berusaha untuk mematuhi skim pensijilan dalam meningkatkan lagi pengurusan kilang ke arah kemampanan dan pengurangan kadar pelepasan gas rumah hijau (GHG). Walau bagaimanapun, skim pensijilan minyak sawit yang sedia ada mempunyai beberapa kekurangan dan batasan yang membebankan industri. Kajian ini memperlihatkan pembangunan jejak karbon kilang minyak sawit dan pengiraan (POMCFA) serta kerangka indeks kelestarian kelapa sawit (POMSI) baharu yang digabungkan dengan alat pemilihan strategi pemulihan. Rangka kerja ini membolehkan pengilang untuk menilai jejak karbon dan prestasi kelestarian kilang kelapa sawit mereka menggunakan satu inventori kilang minyak kelapa sawit. Pertama, kajian ini membangunkan parameter dan indikator POMCFA untuk mengira pelepasan karbon dari kilang tersebut. Pengukuran ini adalah berdasarkan karbon dioksida setara (CO2e). Parameter dan petunjuk POMCFA kemudian digunakan sebagai sebahagian daripada pangkalan data POMSI. Berikutan itu, penilaian POMSI dilakukan menggunakan kaedah pendekatan jarak dekat yang mengukur prestasi kemampanan semasa sesuatu industri dibandingkan dengan sasaran polisi. Prestasi POMCFA diperoleh dari segi jumlah CO2e dan profil GHG. Prestasi POMSI kemudiannya diterjemahkan ke dalam lima sistem penarafan untuk menggambarkan tahap prestasi kemampanan industri iaitu sangat baik, baik, memuaskan, kurang memuaskan, dan sangat kurang memuaskan. Prestasi industri yang setanding diperhatikan menggunakan kaedah grafik. Beberapa kilang minyak kelapa sawit yang dipilih di Malaysia telah digunakan sebagai kajian kes untuk menunjukkan kebolehgunaan kerangka kerja. Berdasarkan dapatan kajian, didapati beberapa penunjuk POMCFA dan POMSI ditahap kurang memuaskan. Dengan mengenal pasti penunjuk yang lemah, cadangan yang mendalam bagi langkah penambahbaikan yang bersepadu telah dicadangkan. Alat pemilihan strategi pemulihan juga telah dihasilkan untuk memilih teknologi yang sesuai untuk memperbaiki kelemahan penunjuk tersebut. Kemudian, skor POMCFA dan POMSI dikira semula untuk menilai keberkesanan strategi pemulihan yang dicadangkan mengenai prestasi kemampanan dan / atau pelepasan CO2e di kilang. Kaedah ini membolehkan industri untuk terus mengukur dan menjejaki prestasi pelepasan dan amalan kemampanan yang dipraktikkan. Penilaian ini memberikan dorongan kepada setiap kilang untuk bersaing ke arah lebih baik dan belajar antara satu sama lain selain berusaha untuk meningkatkan prestasi industri secara keseluruhan. Di samping itu, penilaian komprehensif yang ditawarkan oleh model strategi pemulihan dalam kajian ini menghasilkan analisis yang lebih baik; seterusnya, membantu industri yang berkaitan membuat keputusan untuk terus meningkatkan prestasi dengan penyelesaian keputusan yang optimum.

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LIST OF ABBREVIATIONS

AHP	-	Analytic Hierarchy Process
AMDAL	-	Analisis Mengenai Dampak Lingkungan
AMPL	-	A Mathematical Programming Language
ArcGIS	-	Aeronautical Reconnaissance Coverage Geographic Information System
ASPID	-	Analysis and Synthesis of Parameters Under Information Deficiency
BOD	-	Biological Oxygen Demand
BP	-	Best Performance
cCPO	-	Crude Palm Oil
CKPO	-	Crude Kernel Palm Oil
cKR	-	Kernel
cLO	-	Losses
CO	-	Carbon Monoxide
COD	-	Chemical Oxygen Demand
COST	-	Overall Cost
CPLEX	-	IBM ILOG CPLEX Optimization Studio
CPO	-	Crude Palm Oil
CSPI	-	Composite Sustainable Performance Index
CSR	-	Corporate Social Responsibility
cTC	-	Total Cost
DEFRA	-	Department for Environment, Food and Rural Affairs
DOE	-	Department of Environment
DP	-	Diesel Used for Process
DP	-	Diesel Used for Process
DUC	-	Dust Concentration
DV	-	Diesel Used for Vehicle in Mill
ECO	-	Engagement with Contractor or Vendor
EEM	-	Engagement with Employees
EFB	-	Empty Fruit Bunch Disposed

EG	-	Electric Used by The Mill from Grid
EG	-	Electric Used by The Mill from Grid
ELECTRE	-	Elimination and Choice Translating Reality
ELO	-	No of Engagement Per Year with Local Community
EPA	-	Environmental Protection Agency
EPI	-	Environment Performance Index
EQI	-	Environment Quality Index
ET	-	Electric Used by The Mill from Turbine
EU RED	-	European Union Renewable Energy Directive
FAR	-	Fatality Rate
FAR	-	Fatality Rate
FC	-	Factor Changes
FELDA	-	Federal Land Development Authority
FFB	-	Fresh Fruit Bunch
FRIM	-	Forest Research Institute Malaysia
FRR	-	Frequency Rate
FRR	-	Frequency Rate
GAMS	-	General Algebraic Modeling System
GAP	-	Good Agriculture Practice
GDP	-	Gross Domestic Product
GHG	-	Greenhouse Gas
GIPS	-	Green Industrial Performance Scorecard
GRI	-	Global Reporting Initiatives
HDI	-	The Human Development Index
IBM	-	International Business Machines Corporation
IC	-	Investment Cost
IC	-	Investment Cost
I_{CSD}	-	Composite Sustainable Development Index
INCAM	-	Integrated Carbon Accounting and Mitigation
IR	-	Incident Rate
IR	-	Incident Rate
IRE	-	Integrated Resource-Efficient

ISCC	-	International Sustainability and Carbon Certification
ISDI	-	Indicators of Sustainable Development for Industry
ISP	-	Indicators of Sustainable Production
ISPO	-	Indonesian Sustainable Palm Oil
IT	-	Industry Target
KEL	-	Kernel Losses Per FFB
KER	-	Kernel Extraction Rate
KS	-	FFB From Known Source
LC	-	Level of Consensus
LCA	-	Life Cycle Analysis
LCC	-	Low Carbon Cities
LCCI	-	Low Carbon Indicator
LINDO	-	Linear, Interactive, And Discrete Optimizer
LP	-	Linear Programming
MATLAB	-	Matrix Laboratory
MCAR	-	Malaysia Clean Air Regulations
MCDA	-	Multi-Criteria Decision Analysis
MESMIS	-	Evaluation of Natural Resource Management Systems
MILP	-	Mixed Integer Linear Programming
MINLP	-	Mixed Integer Nonlinear Programming
MOSTI	-	Ministry of Science, Technology And Innovation
MPL	-	Mathematical Programming Language
MPOB	-	Malaysian Palm Oil Board
MPOC	-	Malaysian Palm Oil Council
MRE	-	Mixed Raw Effluent
MRE	-	Palm Oil Mill Effluent
MSGAP	-	Malaysian Standard Good Agricultural Practice
MSGMP	-	Malaysian Standard Good Manufacturing Practice
MSPO	-	Malaysian Sustainable Palm Oil
MSW	-	Municipal Solid Waste
MYCARBON	-	National Level Corporate Ghg Reporting Programme
nAQ	-	Air Quality (Boiler Emission)

nAS	-	Air Surrounding (Only in Johor)
nDIC	-	Diesel Consumption
nEC	-	Electric Consumption
NGO	-	Non-Government Organisations
NID A1*	-	Nitrogen Dioxide Point A1
NID A2*	-	Nitrogen Dioxide Point A2
NLP	-	Nonlinear Programming
NRE	-	Ministry of Natural Resources and The Environment
nWas	-	Waste
nWC	-	Water Consumption
nWW	-	Waste Water
nWWQ	-	Waste Water Quality of Effluent (Final Discharge)
O&G	-	Oil and Grease Content
OER	-	Oil Extraction Rate (Oer)
OIL	-	Oil Losses Per FFB
OSHA	-	Occupational Safety and Health Act
PC	-	Production Cost
PC	-	Production Cost
PFD	-	Process Flow Diagram
PH <*	-	pH Less Than 7
PH >*	-	pH More Than 7
POMCFA	-	Palm Oil Mill Carbon Footprint and Accounting
POME	-	Palm Oil Mill Effluent
POMSI	-	Palm Oil Mill Sustainability Index
PORIM	-	Palm Oil Research Institute of Malaysia
PRC	-	People's Republic of China
PROMETHEE	-	Preference Ranking Organization Method for Enrichment of Evaluations
PS	-	FFB from Peat Soil
PTT	-	Proximity to Target
QCP	-	Quadratic Constrained Programming Solver
QP	-	Quadratic Programming Solver
RA	-	Rainforest Alliance

RSPO	-	Roundtable Sustainable Palm Oil
RTRS	-	Round Table Responsible Soy
SAM	-	Sulfuric Acid Mist
SAM	-	Sustainability Assessment Model
SAN	-	Sustainable Agriculture Network
SD	-	Sustainable Development
SDFI	-	Sustainable Dairy Farming Index
SDS	-	Sulfur Dioxide So_2
SDS A1*	-	Sulfur Dioxide SO2 Point A1
SDS A2*	-	Sulfur Dioxide SO2 Point A2
SIRIM	-	Standard and Industrial Research Institute of Malaysia
SM	-	Safety Meeting
SMART	-	Simple Multi Attribute Rating Technique
sOAC	-	Occupational Accident Case
sOPD	-	Occupational Poisoning and Disease Case
SR	-	Severity Rate
SR	-	Severity Rate
sRF	-	Risk Factor
sSA	-	Safety
sSE	-	Stake Holders Engagements
SUS	-	Suspended Solid
SV	-	Site Verification of Known FFB Source
SWA	-	Simple Weighted Addition Method
TNB	-	Tenaga Nasional Berhad
TOC	-	Total Organic Carbon
TON	-	Total Nitrogen
TOPSIS	-	Technique for Order Preference by Similarity to Ideal Solution
TOS	-	Total Solid
TSP A1*	-	Total Suspended Particulate Point A1
TSP A2*	-	Total Suspended Particulate Point A2
UOW	-	Use of Water
USD	-	United States Dollar

UTM	-	Universiti Teknologi Malaysia
VC	-	Variable Cost
VC	-	Variable Cost
VSD	-	Variable Speed Drive
WA	-	Weighted Average
WIN QSB	-	Windows Quantitative Systems for Business

LIST OF SYMBOLS

aCO_2e	-	Amount of CO_2e emitted for each consumption
$A_{j,l}$	-	Aspect score of the j^{th} mill, i^{th} indicator
C_m	-	Total cost of m^{th} mitigation options
D	-	Monthly consumption or generation
$EFCO_2e$	-	Carbon dioxide equivalent emission factor
F_{mn}	-	Factor changes of the mitigation option, m^{th}, to the indicator, n^{th}
IC_m	-	Investment cost of m^{th} mitigation options
I_j	-	Index score of the j^{th} mill
$max_{(m_{ij})}$	-	Lowest benchmark value of m_{ij} data set
m_{ij}	-	Data value of the jth mill, ith indicator
$min_{(m_{ij})}$	-	Lowest benchmark value of m_{ij} data set
n_{k1}	-	Number of 'not important' of k^{th} parameter
n_{k2}	-	Number of 'least important' of k^{th} parameter
n_{k3}	-	Number of 'less important' of k^{th} parameter
n_{k4}	-	Number of 'important' of k^{th} parameter
n_{k5}	-	Number of 'most important' of k^{th} parameter
$No\ of\ indicator_k$	-	No of indicator in k^{th} parameter
$otCO_2e$	-	Overall total CO_2e Emission
$PAS_{j,k}$	-	Parameter Aggregation Score of the j^{th} mill, k^{th} parameter
PC_m	-	Production cost of m^{th} mitigation options
$P_{j,k}$	-	Parameter score of the j^{th} mill, k^{th} parameter
PTT_{ij}	-	Normalized value for j^{th} mill, i^{th} indicator
tCO_2e_i	-	Total CO_2e Emission for Indicator
tCO_2e_p	-	Total CO_2e Emission for Parameter
tCO_2e_s	-	Total CO_2e Emission for Stream
tCO_2e_{uo}	-	Total CO_2e Emission for Unit Operation
t_i	-	Target value of the i^{th} indicator
VC_m	-	Variable cost of m^{th} mitigation options

W_n	-	Weightage of the indicator, n^{th}
$Weightage_k$	-	Weightage of k^{th} parameter
W_{sumj}	-	Weighted sum of each Parameter
W_{total}	-	Total weight of parameter included
X_m	-	Binary variable for the m^{th} mitigation options
Y_n	-	Requirement set by n^{th} indicator

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Criticisms toward palm oil sustainability practices have risen significantly among consumers and NGOs. Major palm oil consumers such as Starbucks and Ferrero Corp. require the palm oil production process to be practised in a balanced environmental, economic, and socially-acceptable manner so that their products will continue to be accepted in the current market (Mazzoni, 2014). The importance of the issue of sustainability in the industry truly increased when the European Parliament decided to ban the use of palm oil in their biofuels by 2020, citing sustainable concerns (Hannah Ellis-Petersen, 2018). This action has put more pressure on the industry to not only produce sustainable palm oil but to create a platform to stand up against the accusations made towards palm oil.

In the palm oil arena, Malaysia has served as a role model for its neighbouring countries such as Indonesia, The Philippines, and Thailand (Awalludin *et al.*, 2015). Global production is soaring, as palm oil is the highest-yielding vegetable oil crop (Giller *et al.*, 2017). The vast 85% majority of palm oil in the world comes from Malaysia and Indonesia, which have increased the total capacity of palm oil mill by 128% over the last decade to 58 million tonnes per year. Its 28% global trade dominance of palm oil in the vegetable oil market in 2013 propelled Malaysia to become the world's second-largest palm oil producer (Chow, 2019).

This advancement, however, comes at a cost. In particular, the public and consumer concerns of the sustainability of palm oil have increased (Alang Mahat, 2012). This issue is a constant debate among governments, the industry, and its consumers (Singh *et al.*, 2007). In addition, people are also questioning the amount of greenhouse gas (GHG) emissions originating from palm oil mills. Therefore, the issue of sustainability has serious implications for the palm oil industry. At the same time, based on EPA (2014) statistics, greenhouse gas emissions totalled 6,870 million metric tonnes of carbon dioxide equivalent, contributing 82% of total GHGs with 77% coming from industries and the electricity and transportation sectors. The responsibility to ensure the sustainability issues now seem to be pointed towards palm oil-producing countries, particularly Malaysia and Indonesia, the largest palm oil producers in the world.

The sustainability issue can threaten Malaysia's economy, as the palm oil industry contributes 5% to 7% of the country's gross domestic product (GDP), raking in a yearly average of RM64.24 billion in export revenue for the last five years. The industry has also created jobs for about 650,000 farmers and has increased the potential for foreign labourers. In fact, this industry is the 4^{th} largest contributor to Malaysia's economy. The ban on palm oil will affect the country's productive resources, economy, and production.

In reality, of all the vegetable oils, palm oil is the most efficient, producing up to 30% more product for the amount of land needed for the plantation (Oil World, 2017). Palm oil yield is ten times more than other crops. From Figure 1.1, it can be seen that with only 6.6% of land use, the palm oil crop can produce up to 38.7% palm oil output, as shown in Figure 1.2. Because of the crop efficiency, the palm oil price is much lower than other vegetable oils, as shown in Figure 1.3. However, due to mass production and a huge demand, palm oil has been painted as the culprit in the degradation of the environment, economy, and social.

As a major palm oil producer, Malaysia needs to respond to the above issue; the industry must measure its move towards sustainable practices (Azapagic and Perdan, 2000) and assess the carbon emissions of palm oil mills not only to counter the stigma towards palm oil practices but also to remain competitive in the market.

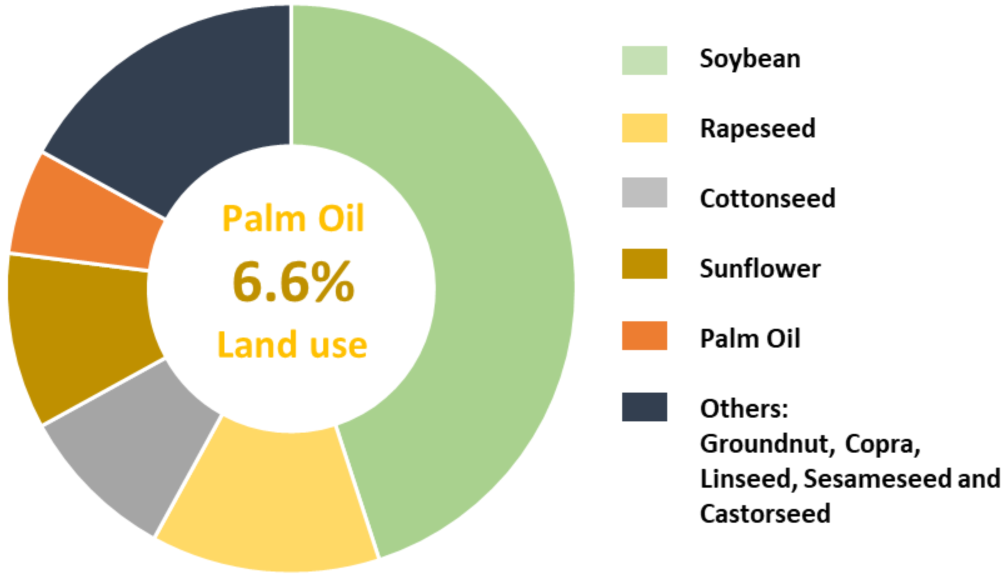

Figure 1.1 Major Oilseeds: Area in 2015 (Total is 274.4 million hectares) (Oil World 2016)

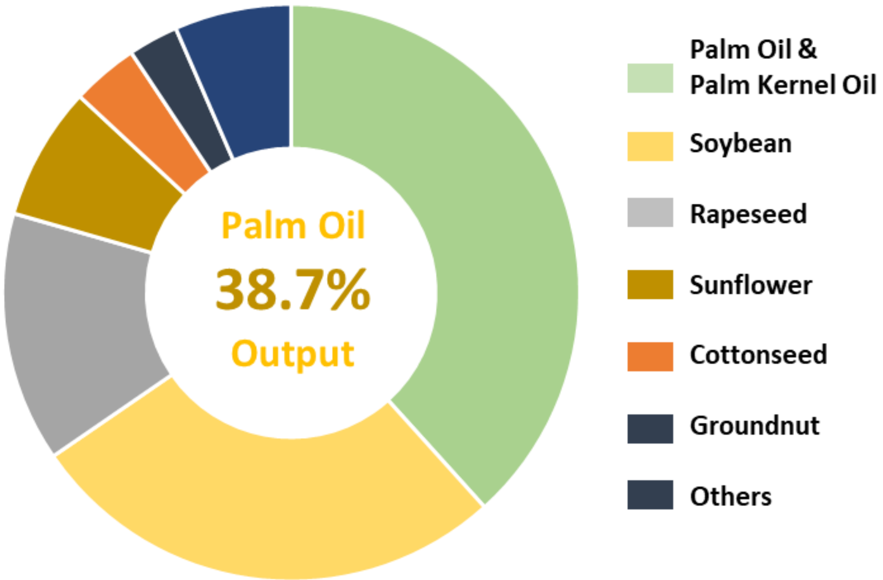

Figure 1.2 Global production of oils and fats in 2015 (Total is 179.6 million tons) (Oil World 2016)

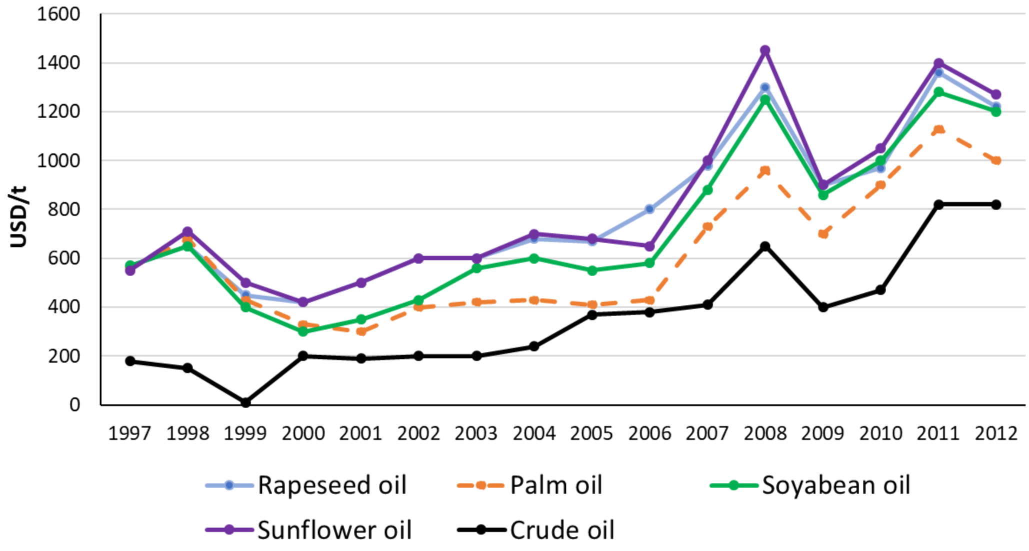

Figure 1.3 Price comparison of selected vegetable oil (Abdullah, 2013)

In current practice, applying for certification schemes is the main way to demonstrate the performance of the palm oil mill carbon release and sustainability practices. Another approach was given by Malaysia's National Corporate GHG Reporting Programme (MYCarbon), which proposes a national standard for emission measurement and calculation. However, carbon-related assessments entail more drawbacks that could shift the problem, e.g. reductions in carbon accounting are obtained at the expense of an increase in other sustainability impacts.

The closest things to a comprehensive measurement are the Roundtable on Sustainable Palm Oil (RSPO), the Indonesian Sustainable Palm Oil (ISPO) certification, and the International Sustainability and Carbon Certification (ISCC). Malaysia is also paving the way with its national certification standard, the Malaysian Sustainable Palm Oil (MSPO) scheme. However, these schemes still have limitations, as they require qualitative assessment and non-measurable valuation, making it difficult for the palm oil industry to conduct analysis and identify weaknesses in performance (Lim and Biswas, 2018).

The issue becomes more complicated because the industries are obligated to submit various reports to different bodies such as the RSPO for sustainability certification and MYCarbon for the carbon emission reports. With the absence of a systematic tool, industries face difficulties gathering and analysing data. For example, one of the largest palm oil producers in Malaysia, Federal Land Development Authority (FELDA), pulled out from applying for the RSPO in 2016 due to the difficulty to comply with the procedure of the certification schemes (Ooi, 2016). Furthermore, in 2013, only 38% of palm oil production are certified sustainable by these schemes (King and Mike, 2013).

To maintain a commitment to sustainable practices, a comprehensive assessment is a must for the valuation of an advanced mitigation plan to help reduce and overcome any shortcomings that mills face. A systematic decision support tool that evaluates possible alternatives to overcome weaknesses in operations could assist decision-makers to arrive at optimal solutions. As contended by Hjorth and Bagheri (2006) "There is an emerging understanding that the quality of a decision making process is absolutely critical for the achievement of an effective product in the decision". However, an assessment tool that offers mitigation strategies to improve decision-making regarding operational weaknesses is yet to be established.

1.2 Problem Statement

Palm oil demand is constantly expanding year by year because of its high yield ability and lower cost. The industry is estimated to produce more than 50 billion kilograms of palm oil every day. However, with such a large amount, debate on whether palm oil is sustainably produced has emerged. Palm oil production is, moreover, criticised for its high GHG impact. At the mill level, two main sources of GHG emissions are present, namely due to the fossil fuel consumption and methane emission from the palm oil mill effluent (POME) in open anaerobic lagoons (although only the latter is significant at the supply chain level (Hosseini and Wahid, 2015).

The responsibility for this issue seems to point towards palm-oil producing countries, particularly Malaysia and Indonesia, which are the world's largest palm oil producers. The issue has become increasingly vital for the industry, as major palm oil consumers such as Starbucks and Ferrero Corporation have stated that they will only use certified palm oil in their production by 2015. To make it worse, the European Parliament has planned to ban the use of palm oil in their biofuels by 2020 (Hannah Ellis-Petersen, 2018). A ban on palm oil, one of Malaysia's major exports, will affect the country's productive resources, economy, and production. Malaysia is the world's second-largest palm oil producer, so it needs to keep track of sustainability practices starting from the miller, transporter, and the refiner to the end-user, not only to counter the perception towards palm oil practices but also to remain competitive in the market.

Currently, applying for certification schemes is the main method to assess the performance of carbon emissions and sustainability practices of palm oil mills. The more commonly used carbon reporting methods in Malaysia are MYCarbon and ISCC while related international sustainability certification schemes include RSPO, ISPO, etc. Recently, Malaysia is also paving the way with its own national certification standard, the MSPO scheme. However, carbon-related assessments are a poor representative of a comprehensive analysis (Laurent *et al.*, 2012) while sustainability-related schemes still have limitations, as they involve qualitative assessment and non-measurable valuation, making it difficult for the industries to conduct analyses and identify weaknesses in the mill performance (Lim and Biswas, 2018).

With the absence of a systematic tool, industries face difficulties gathering and analysing data and the issue becomes more complicated because the industries are obligated to submit various reports to different bodies such as sustainability certifications to RSPO and carbon emission reports to MYCarbon. To reflect their commitment to maintaining sustainable practices, an advanced mitigation planning tool is necessary. A systematic selection tool for identifying appropriate mitigation strategies to target specific weaknesses will be able to assist decision-makers to arrive at an optimal solution to their problems. However, an assessment offering a mitigation strategy decision tool to improve decision-making regarding operational weaknesses is yet to be established. The limitations of the current palm oil assessment are listed below:

Carbon footprint accounting has limitations in representing a comprehensive assessment and may result in an inaccurate selection of further mitigation strategies.

The current assessment is subjective and does not provide specific guidelines to be followed. Besides, there is an unsystematic data collection process for the palm oil industry, making the assessment process tougher. Therefore, the palm oil industry needs a systematic quantitative assessment tool to manage its data efficiently and facilitate its assessments.

The palm oil industry lacks a self-assessment tool to measure its sustainability performance. This self-assessment is important as a preparation before the certification assessment. Thus, a sustainability index method will help profile the sustainability of the industry besides highlighting the potential improvement in sustainable performance via a graphical method.

A stand alone assessment requires the industry to implement different assessment systems to assess different parameters such as sustainability and carbon emissions with each assessment costing a huge amount. Thus, an integrated assessment system will help reduce the cost of measuring different parameters.

This study introduced the index concept to systematically develop a database and a self-assessment tool for the palm oil industry that highlights the necessary improvements required based on graphical results. Although various sustainability assessment schemes have been introduced, the literature indicates a lack of an integrated assessment with quantifiable results. This study proposes the development of an integrated framework incorporating sustainability and carbon footprint assessment using an index method. This system will provide the palm oil industry with a systematic database, besides assisting the industry to perform its own assessment and improve upon identified weaknesses.

The absence of integrated assessment and analysis, it would be impossible to develop a mitigation selection tool. Studies on the development of a mitigation selection tool for the palm oil sector is somehow still scarce. Therefore, this study proposes the development of a new framework to integrate the quantitative assessment of carbon footprint and sustainability, including a mitigation selection model to help provide optimal alternatives for identified weaknesses.

1.3 Research Objectives

Based on the problem statements, the main objective of this work is to develop a framework that integrates carbon footprint accounting, sustainability performance assessment, and a mitigation strategy selection tool for palm oil mill. There are three objectives for completing this framework:

1. To develop a method for the palm oil mill carbon footprint and accounting assessment (POMCFA).
2. To develop a method to assess palm oil mill sustainability performance (POMSI).
3. To develop a mathematical model formulated as a Mixed Integer Linear Programme (MILP) for integrated mitigation measures.

1.4 Scope of Study

To achieve the research objectives, the scope of work was delineated as follows:

1. A method to calculate carbon footprint and accounting was developed for the palm oil mill industry.
   (a) All the indicators, criteria, and regulations are limited to the palm oil mill only.
   (b) To identify applicable carbon footprint indicators for palm oil mills
   (c) To perform an analysis and propose improvements of POMCFA

2. A method to assess sustainability performance was developed for the palm oil mill industry.

(a) The sustainability database was structured based on three aspects—environment, economy, and social.

(b) Data collection was limited to palm oil agencies (ex: MPOB, DOE, FELDA), palm oil mill operations, processes, and management.

(c) To establish a sustainability index and an assessment calculation method for palm oil mills

3. The mitigation selection model for the carbon and sustainability assessment:

(a) Optimal mitigation planning that corresponds to the minimum cost are determined while maintaining or enhancing CO_2 emissions and the sustainability performance score.

(b) The mitigation proposed was based on a literature study but limited to environmental and economic aspects.

(c) The model was coded in General Algebraic Modelling System (GAMS) software.

(d) Analysis was performed and improvements was proposed by considering the integrated parameters of POMCFA and POMSI

1.5 Significance of Study

This study involved the integration of carbon accounting and sustainability index assessments for a palm oil mill into one single framework.

1. The framework enables a comprehensive assessment to quantify and monitor carbon footprint, to assist the palm oil industry to collect, analyse, and transform sustainability data into meaningful information with respect to standard regulations.

2. Industries can convince other parties of their carbon level and sustainable practices in compliance with the standard.

3. A standard framework also enables the industry to monitor its sustainability performance and carbon footprint as an internal benchmark or to compare it with other palm oil producers.

4. From the analysis of the framework, the industries will be able to identify weaknesses in sustainability and carbon emissions simultaneously.

5. An integrated analysis of the assessment can provide a bigger picture of the current practice and help the management arrive at more accurate decisions.

6. A decision tool for alternative improvements was also developed to help decision-makers obtain more effective solutions regarding the problem.

1.6 Organisation of Thesis

Chapter 1 provides the introduction and background of the palm oil industry, addresses the issues of current assessments in the palm oil sector. It also presents the problem statement, research goal, scope of study, and significance of study.

Chapter 2 provides a background on the palm oil industry including an overview of the palm oil industry, general sustainability assessments, and current palm oil sustainability assessments. Quantitative approaches to sustainability assessment are also discussed. Previous studies on mitigation strategy selection models are also presented.

Chapter 3 represents an overview of the methodology for the study to achieve the research objectives. The methodology contains five parts, which are the development of palm oil mill carbon footprint and accounting (POMCFA), the POMCFA results and analysis, the development of a palm oil mill sustainability index (POMSI), the POMSI results, and the analysis and integrated mitigation strategy selection model for POMCFA and POMSI.

Chapter 4 presents a case study of the application of POMCFA and POMSI for the sustainability assessment of a palm oil mill but without considering the mitigation strategy yet. This study was conducted in a palm oil mill in Malaysia in 2015.

Last but not least chapter 5 shows case study 2 which considers the solution for improving the performance of POMCFA and POMSI using the mitigation strategy model by suggesting the optimal selection to fix identified hotspots. This case study is an extension of the first case study presented in Chapter 4; it adds the selection of the mitigation strategy for the identified hotspot for both assessments.

Lastly, chapter 6 concludes the key contributions of this research and provides recommendations for possible future work.

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Appendix A

Sample of Questionnaire

Invitation to Participate In Weight Assignment Survey for Palm Oil Mill Sustainability Index (POMSI) 2016

YBhg. Tan Sri/Dato' Seri/Professor/Assoc. Prof./Dr./Datuk/Dato/Datin/Tuan/Puan

Felda Global Venture (FGV) with cooperation Universiti Teknologi Malaysia (UTM) has been developing the Palm Oil Mill Sustainability Index (POMSI) for Felda palm oil mill. POMSI represents a comprehensive performance system of palm oil mill on three important aspects: Environment, Economy and Social. The POMSI for Felda is constructed through the calculation and aggregation of 48 indicators reflecting Felda palm oil mill data. These indicators are combined into 22 parameters, each of which fit under one of three overarching objectives: Environment, Economy and Social. Calculation and aggregation of POMSI involve computation of proximity-to-target (PTT) score and weightage assigned to the parameters. While PTT score reflects how close a palm oil mill from the designated target or desired conditions of the mill, the weight assigned to each indicator reflects relative importance of the indicators as perceived by palm oil mill expert. Assigning weight to indicators is important for parameter because of different impact, importance and policy reason associated with each indicator.

We would like to invite you to kindly participate in a survey on how environmental experts in FELDA perceived relative importance of mill issues pertaining to POMSI. Results of the survey will form the basis for our team to decide on weightage of the indicators needed for calculation of POMSI for FELDA.

Thank you for participating.

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Kindly tick (/) your choice on the scale of importance where 1 represents not important and increase in importance up to 5 very important:

1 = not important

2 = less important

3 = not so important

4 = important

5 = very important

Parameters	Rating				
	1	2	3	4	5
Water Consumption					
Air Quality (Boiler Emission)					
Air Surrounding (only in johor)					
Waste					
Waste water					
Waste Water Quality of Effluent (final discharge)					
Diesel Consumption					
Electric Consumption					
FFB					
Kernel					
Losses					
Total Cost					
Risk Factor					
Safety					
Occupational Poisoning and Disease Case					
Occupational Accident Case					
Stake Holders Engagements					

Appendix B

Monthly Consumption of Mill A, B, C and D

Mill A

Unit Operation, uo			from gate to process inlet	sterilization		stripping	dilution	seperation of kernel and shell from nut							deoiled fiber	removal of fibrous tailings	crude oil tank	removal of sludge and solids from oil			
Parameter	**Indicator**	**Unit**	Stream, s																		
			U1	S2	S3	S6	S10b	S11b	S11h	S11i	S11j	S11k	S11L	S11m	S11p	S12	S13	S14	S14b	S14c	S14d
Water Consumption	Use of fresh water	m3					0.16									0.16	0.16	0.16	0.16	0.16	
Air Quality (Boiler Emission)	Dust Concentration @ 12% CO_2 +PM10 +PM2.5	g/Nm^3			0.01																
	Sulfuric Acid Mist	g/Nm^3			0.0001																
	Sulfur Dioxide SO_2	g/Nm^3			0.0008																
Waste	Empty fruit bunch	t				0.12															
Waste water	Palm Oil Mill Effluent	t		0.19				0.0116	0.032	0.010	0.007	0.003	0.00008	0.007							0.26
Diesel Consumption	Diesel used for Process	L													0.3						
	Diesel used for Vehicle in mill	L	0.175																		
Electric Consumption	Electric used by the mill from grid	kwh	0.012																		

Mill B

Unit Operation, uo			from gate to process inlet	sterilization		stripping	dilution	seperation of kernel and shell from nut							deoiled fiber	removal of fibrous tailings	crude oil tank	removal of sludge and solids from oil			
Parameter	**Indicator**	**Unit**	Stream, s																		
			U1	S2	S3	S6	S10b	S11b	S11h	S11i	S11j	S11k	S11L	S11m	S11p	S12	S13	S14	S14b	S14c	S14d
Water Consumption	Use of fresh water	m3					0.20									0.20	0.20	0.20	0.20	0.20	
Air Quality (Boiler Emission)	Dust Concentration @ 12% CO2 +PM10 +PM2.5	g/Nm^3			0.43																
	Sulfuric Acid Mist	g/Nm^3			0.0001																
	Sulfur Dioxide SO_2	g/Nm^3			0.0001																
Waste	Empty fruit bunch	t				0.11															
Waste water	Palm Oil Mill Effluent	t		0.24				0.0147	0.040	0.012	0.009	0.003	0.00010	0.009							0.33
Diesel Consumption	Diesel used for Process	L													0.33						
	Diesel used for Vehicle in mill	L	0.17																		
Electric Consumption	Electric used by the mill from grid	kwh	0.02																		

Mill C

Unit Operation, uo			from gate to process inlet	sterilization		stripping	dilution	seperation of kernel and shell from nut							deoiled fiber	removal of fibrous tailings	crude oil tank	removal of sludge and solids from oil			
Parameter	**Indicator**	**Unit**	Stream, s																		
			U1	S2	S3	S6	S10b	S11b	S11h	S11i	S11j	S11k	S11L	S11m	S11p	S12	S13	S14	S14b	S14c	S14d
Water Consumption	Use of fresh water	m3					0.17									0.17	0.17	0.17	0.17	0.17	
Air Quality (Boiler Emission)	Dust Concentration @ 12% CO2 +PM10 +PM2.5	g/Nm^3			0.47																
	Sulfuric Acid Mist	g/Nm^3			0.1																
	Sulfur Dioxide SO_2	g/Nm^3			0.2000																
Waste	Empty fruit bunch	t				0.06															
Waste water	Palm Oil Mill Effluent	t		0.28				0.0171	0.047	0.014	0.010	0.004	0.00011	0.010							0.39
Diesel Consumption	Diesel used for Process	L													0.53						
	Diesel used for Vehicle in mill	L	0.17																		
Electric Consumption	Electric used by the mill from grid	kwh	0.06																		

Mill D

Unit Operation, uo			from gate to process inlet	sterilization		stripping	dilution	seperation of kernel and shell from nut						deoiled fiber	removal of fibrous tailings	crude oil tank	removal of sludge and solids from oil			
			Stream, s																	
Parameter	**Indicator**	**Unit**	U1	S2	S3	S6	S10b	S11b	S11h	S11i	S11j	S11k	S11L	S11m	S11p	S12	S13	S14	S14b	S14c	S14d
Water Consumption	Use of fresh water	m3					0.18									0.18	0.18	0.17	0.17	0.17	
Air Quality (Boiler Emission)	Dust Concentration @ 12% CO2 +PM10 +PM2.5	g/Nm^3			0.019																
	Sulfuric Acid Mist	g/Nm^3			0.0002																
	Sulfur Dioxide SO_2	g/Nm^3			0.0005																
Waste	Empty fruit bunch	t				0.05															
Waste water	Palm Oil Mill Effluent	t		0.25				0.0156	0.043	0.013	0.009	0.003	0.00010	0.009							0.35
Diesel Consumption	Diesel used for Process	L													0.4						
	Diesel used for Vehicle in mill	L	0.16																		
Electric Consumption	Electric used by the mill from grid	kwh	0.05																		

Appendix C

Emission Data, CO_2e for each Indicator and Stream for Mill A, B, C and D

Mill A

Aspect	Parameter	Symbol	Indicator	Symbol	Diesel Utilization	Sterilization		Stripping	Dilution	Seperation of Kernel and Shell from Nut							Deoiled Fiber	Removal of Fibrous Tailings	Crude Oil Tank	Removal of Sludge and Solids from Oil			
					U1	S2	S3	S6	S10b	S11b	S11h	S11i	S11j	S11k	S11L	S11m	S11p	S12	S13	S14	S14b	S14c	S14d
Environment	Water Consumption	nWC	Use of Fresh Water	UOW					0.0540									0.0539	0.0539	0.0537	0.0537	0.0537	
	Air Quality (Boiler Emission)	nAQ	Dust Concentration @ 12% CO_2 +PM10 +PM2.5	DUC			0.0077																
			Sulfuric Acid Mist	SAM			0.0002																
			Sulfur Dioxide SO_2	SDS			0.0015																
	Waste	nWAS	Empty Fruit Bunch	EFB				0.1320															
	Waste water	nWW	Palm Oil Mill Effluent	MRE		3.3718				0.2075	0.5719	0.1716	0.1258	0.0458	0.0014	0.1244							4.7138
	Diesel Consumption	nDIC	Diesel used for Process	DP													0.9390						
			Diesel used for Vehicle in Mill	DV	0.5478																		
	Electric Consumption	nEC	Electric used by the Mill from Grid	EG	0.0067																		

Mill B

Aspect	Parameter	Symbol	Indicator	Symbol	Diesel Utilization	Sterilization		Stripping	Dilution	Seperation of Kernel and Shell from Nut							Deoiled Fiber	Removal of Fibrous Tailings	Crude Oil Tank	Removal of Sludge and Solids from Oil			
					U1	S2	S3	S6	S10b	S11b	S11h	S11i	S11j	S11k	S11L	S11m	S11p	S12	S13	S14	S14b	S14c	S14d
Environment	Water Consumption	nWC	Use of Fresh Water	UOW					0.0671									0.0670	0.0670	0.0667	0.0667	0.0667	
	Air Quality (Boiler Emission)	nAQ	Dust Concentration @ 12% CO_2 +PM10 +PM2.5	DUC			0.3311																
			Sulfuric Acid Mist	SAM			0.0002																
			Sulfur Dioxide SO_2	SDS			0.0002																
	Waste	nWAS	Empty Fruit Bunch	EFB				0.1210															
	Waste water	nWW	Palm Oil Mill Effluent	MRE		4.2796				0.2634	0.7259	0.2178	0.1597	0.0581	0.0017	0.1580							5.9828
	Diesel Consumption	nDIC	Diesel used for Process	DP													1.0329						
			Diesel used for Vehicle in Mill	DV	0.5321																		
	Electric Consumption	nEC	Electric used by the Mill from Grid	EG	0.0112																		

Mill C

Aspect	Parameter	Symbol	Indicator	Symbol	Diesel Utilization	Sterilization		Stripping	Dilution	Seperation of Kernel and Shell from Nut							Deoiled Fiber	Removal of Fibrous Tailings	Crude Oil Tank	Removal of Sludge and Solids from Oil			
					U1	S2	S3	S6	S10b	S11b	S11h	S11i	S11j	S11k	S11L	S11m	S11p	S12	S13	S14	S14b	S14c	S14d
Environment	Water Consumption	nWC	Use of Fresh Water	UOW					0.0591									0.0590	0.0590	0.0588	0.0588	0.0588	
	Air Quality (Boiler Emission)	nAQ	Dust Concentration @ 12% CO_2 +PM10 +PM2.5	DUC			0.3619																
			Sulfuric Acid Mist	SAM			0.1840																
			Sulfur Dioxide SO_2	SDS			0.3680																
	Waste	nWAS	Empty Fruit Bunch	EFB				0.0660															
	Waste water	nWW	Palm Oil Mill Effluent	MRE		4.9929				0.3073	0.8469	0.2541	0.1863	0.0678	0.0020	0.1843							6.9800
	Diesel Consumption	nDIC	Diesel used for Process	DP													1.6589						
			Diesel used for Vehicle in Mill	DV	0.5321																		
	Electric Consumption	nEC	Electric used by the Mill from Grid	EG	0.0337																		

Mill D

Aspect	Parameter	Symbol	Indicator	Symbol	Diesel Utilization	Sterilization		Stripping	Dilution	Seperation of Kernel and Shell from Nut							Deoiled Fiber	Removal of Fibrous Tailings	Crude Oil Tank	Removal of Sludge and Solids from Oil			
					U1	S2	S3	S6	S10b	S11b	S11h	S11i	S11j	S11k	S11L	S11m	S11p	S12	S13	S14	S14b	S14c	S14d
Environment	Water Consumption	nWC	Use of Fresh Water	UOW					0.0597									0.0596	0.0596	0.0594	0.0594	0.0594	
	Air Quality (Boiler Emission)	nAQ	Dust Concentration @ 12% CO_2 +PM10 +PM2.5	DUC			0.0146																
			Sulfuric Acid Mist	SAM			0.0004																
			Sulfur Dioxide SO_2	SDS			0.0009																
	Waste	nWAS	Empty Fruit Bunch	EFB				0.0572															
	Waste water	nWW	Palm Oil Mill Effluent	MRE		4.5390				0.2794	0.7699	0.2310	0.1694	0.0616	0.0018	0.1675							6.3454
	Diesel Consumption	nDIC	Diesel used for Process	DP													1.2520						
			Diesel used for Vehicle in Mill	DV	0.5008																		
	Electric Consumption	nEC	Electric used by the Mill from Grid	EG	0.0281																		

Appendix D

Total CO_2e for Indicator, Parameter and GHGs Profile for Mill A, B, C and D

Mill A

Aspect	Parameter	Symbol	Total CO_2e Emission for Indicator (kg)	Indicator	Symbol	Total CO_2e Emission for parameter (kg)
Environment	Water Consumption	nWC	0.3230	Use of Fresh Water	UOW	0.3230
	Air Quality (Boiler Emission)	nAQ	0.0077	Dust Concentration @ 12% CO_2 +PM10 +PM2.5	DUC	0.0094
			0.0002	Sulfuric Acid Mist	SAM	
			0.0015	Sulfur Dioxide SO_2	SDS	
	Waste	nWAS	0.1320	Empty Fruit Bunch	EFB	0.1320
	Waste water	nWW	9.3340	Palm Oil Mill Effluent	MRE	9.3340
	Diesel Consumption	nDIC	0.9390	Diesel used for Process	DP	1.4868
			0.5478	Diesel used for Vehicle in Mill	DV	
	Electric Consumption	nEC	0.0067	Electric used by the Mill from Grid	EG	0.0067

Mill B

Aspect	Parameter	Symbol	Total CO_2e Emission for Indicator (kg)	Indicator	Symbol	Total CO_2e Emission for parameter (kg)
Environment	Water Consumption	nWC	0.4012	Use of Fresh Water	UOW	0.4012
	Air Quality (Boiler Emission)	nAQ	0.3311	Dust Concentration @ 12% CO_2 +PM10 +PM2.5	DUC	0.3315
			0.0002	Sulfuric Acid Mist	SAM	
			0.0002	Sulfur Dioxide SO_2	SDS	
	Waste	nWAS	0.1210	Empty Fruit Bunch	EFB	0.1210
	Waste water	nWW	11.8470	Palm Oil Mill Effluent	MRE	11.8470
	Diesel Consumption	nDIC	1.0329	Diesel used for Process	DP	1.5650
			0.5321	Diesel used for Vehicle in Mill	DV	
	Electric Consumption	nEC	0.0112	Electric used by the Mill from Grid	EG	0.0112

Mill C

Aspect	Parameter	Symbol	Total CO_2e Emission for Indicator (kg)	Indicator	Symbol	Total CO_2e Emission for parameter (kg)
Environment	Water Consumption	nWC	0.3536	Use of Fresh Water	UOW	0.3536
	Air Quality (Boiler Emission)	nAQ	0.3619	Dust Concentration @ 12% CO_2 +PM10 +PM2.5	DUC	0.9139
			0.1840	Sulfuric Acid Mist	SAM	
			0.3680	Sulfur Dioxide SO_2	SDS	
	Waste	nWAS	0.0660	Empty Fruit Bunch	EFB	0.0660
	Waste water	nWW	13.8215	Palm Oil Mill Effluent	MRE	13.8215
	Diesel Consumption	nDIC	1.6589	Diesel used for Process	DP	2.1910
			0.5321	Diesel used for Vehicle in Mill	DV	
	Electric Consumption	nEC	0.0337	Electric used by the Mill from Grid	EG	0.0337

Mill D

Aspect	Parameter	Symbol	Total CO_2e Emission for Indicator (kg)	Indicator	Symbol	Total CO_2e Emission for parameter (kg)
Environment	Water Consumption	nWC	0.3570	Use of Fresh Water	UOW	0.3570
	Air Quality (Boiler Emission)	nAQ	0.0146	Dust Concentration @ 12% CO_2 +PM10 +PM2.5	DUC	0.0159
			0.0004	Sulfuric Acid Mist	SAM	
			0.0009	Sulfur Dioxide SO_2	SDS	
	Waste	nWAS	0.0572	Empty Fruit Bunch	EFB	0.0572
	Waste water	nWW	12.5650	Palm Oil Mill Effluent	MRE	12.5650
	Diesel Consumption	nDIC	1.2520	Diesel used for Process	DP	1.7528
			0.5008	Diesel used for Vehicle in Mill	DV	
	Electric Consumption	nEC	0.0281	Electric used by the Mill from Grid	EG	0.0281

Appendix E

Total CO_2e for each Stream, Unit Operation and GHGs Profile for Mill A, B, C and D

Mill A

Unit Operation, uo	Diesel Utilization	Sterilization		Stripping	Dilution	Seperation of Kernel and Shell from Nut							Deoiled Fiber	Removal of Fibrous Tailings	Crude Oil Tank	Removal of Sludge and Solids from Oil			
Total CO_2e for each Operation Unit, (kg)	0.554	3.381		0.132	0.054	1.248							0.939	0.054	0.054	4.875			
Stream, s	**U1**	**S2**	**S3**	**S6**	**S10b**	**S11b**	**S11h**	**S11i**	**S11j**	**S11k**	**S11L**	**S11m**	**S11p**	**S12**	**S13**	**S14**	**S14b**	**S14c**	**S14d**
Total CO_2e for each Stream, (kg)	0.5545	3.3718	0.0094	0.1320	0.0540	0.2075	0.5719	0.1716	0.1258	0.0458	0.0014	0.1244	0.9390	0.0539	0.0539	0.0537	0.0537	0.0537	4.7138

Mill B

Unit Operation, uo	Diesel Utilization	Sterilization		Stripping	Dilution	Seperation of Kernel and Shell from Nut							Deoiled Fiber	Removal of Fibrous Tailings	Crude Oil Tank	Removal of Sludge and Solids from Oil			
Total CO_2e for each Operation Unit, (kg)	0.543	4.611		0.121	0.067	1.585							1.033	0.067	0.067	6.183			
Stream, s	**U1**	**S2**	**S3**	**S6**	**S10b**	**S11b**	**S11h**	**S11i**	**S11j**	**S11k**	**S11L**	**S11m**	**S11p**	**S12**	**S13**	**S14**	**S14b**	**S14c**	**S14d**
Total CO_2e for each Stream, (kg)	0.5433	4.2796	0.3315	0.1210	0.0671	0.2634	0.7259	0.2178	0.1597	0.0581	0.0017	0.1580	1.0329	0.0670	0.0670	0.0667	0.0667	0.0667	5.9828

Mill C

Unit Operation, uo	Diesel Utilization	Sterilization		Stripping	Dilution	Seperation of Kernel and Shell from Nut							Deoiled Fiber	Removal of Fibrous Tailings	Crude Oil Tank	Removal of Sludge and Solids from Oil			
Total CO_2e for each Operation Unit, (kg)	0.566	5.907		0.066	0.059	1.849							1.659	0.059	0.059	7.156			
Stream, s	U1	S2	S3	S6	S10b	S11b	S11h	S11i	S11j	S11k	S11L	S11m	S11p	S12	S13	S14	S14b	S14c	S14d
Total CO_2e for each Stream, (kg)	0.5658	4.9929	0.9139	0.0660	0.0591	0.3073	0.8469	0.2541	0.1863	0.0678	0.0020	0.1843	1.6589	0.0590	0.0590	0.0588	0.0588	0.0588	6.9800

Mill D

Unit Operation, uo	Diesel Utilization	Sterilization		Stripping	Dilution	Seperation of Kernel and Shell from Nut							Deoiled Fiber	Removal of Fibrous Tailings	Crude Oil Tank	Removal of Sludge and Solids from Oil			
Total CO_2e for each Operation Unit, (kg)	0.529	4.555		0.057	0.060	1.681							1.252	0.060	0.060	6.524			
Stream, s	U1	S2	S3	S6	S10b	S11b	S11h	S11i	S11j	S11k	S11L	S11m	S11p	S12	S13	S14	S14b	S14c	S14d
Total CO_2e for each Stream, (kg)	0.5289	4.5390	0.0159	0.0572	0.0597	0.2794	0.7699	0.2310	0.1694	0.0616	0.0018	0.1675	1.2520	0.0596	0.0596	0.0594	0.0594	0.0594	6.3454

Appendix F

Technology Review used in Case Study

	Mitigation strategy technology, m	Main treatment	Cost ($/ton CPO/year)			Total Cost, C_m	Indicator, n												References
							Emission							Consumption or production				Yield	
			IC_m	PC_m	VC_m	TC_m	CH4	N2O	SO2	NOX	VOC	CO	PM	EFB	Fiber	EG	DIP	CPO	
1	EFB combustion	EFB treatment	61.3	34.6	44.7	140.6	-0.005	-0.15											(Saswattecha *et al.*, 2016)
2	EFB pellets production		9.3	25.3	-44.4	-9.8								0.9					(Chiew and Shimada, 2013; Chavalparit *et al.*, 2006)
3	EFB composting plant		2	1.9	-5.3	-1.4								0.9					(Singh *et al.*, 2010)
4	Ethanol production		258.7		-231.5	27.2													(Chiew and Shimada, 2013)
5	Pellets production		9.3	25.3	-44.4	-9.8													(Chavalparit *et al.*, 2006; Chiew and Shimada, 2013)
6	Composting plant		2	1.9	-5.3	-1.4													(Schuchardt *et al.*, 2008; Schuchardt *et al.*, 2002)

7	Selective catalytic reduction	NO_x control for fiber combustion	2.5	1.5		4		-0.08		0.8									(Kim, 2013)
8	Selective non catalytic reduction		1.9	1.1		3		-0.08		0.4									(Mendoza-Covarrubias *et al.*, 2011)
9	Low NOx burner		0.6	0.4		1				0.3									(Cox and Blaszczak, 1999)
10	Non thermal plasma		3.6	0.9		4.5				0.9									(EPA, 2005a; EPA, 2005b)
11	Oil recovery from decanter	Oil extraction improvement			-42	-42												0.055	(Chavalparit, 2006; DEDE, 2006)c
12	Oil recovery from fiber				-7.6	-7.6												0.01	(Chavalparit, 2006; DEDE, 2006)c
13	Oil recovery from EFB				-3.8	-3.8												0.05	(Chavalparit, 2006; DEDE, 2006)c
14	Oil recovery from POME		0.4	0.2	-3.9	-3.3												0.05	(Chavalparit, 2006; DEDE, 2006)c
15	Cyclones	PM control for fiber combustion	0.4	0.2		0.6							0.8						(EPA, 2003b)
16	Baghouse		0.3	0.1		0.4							0.99						(EPA, 2003a)
17	Electrostatic precipitator		1.1	0.6		1.7							0.99						(EPA, 2003c)
18	Biogas plant	POME treatment	8.2	5.8	-3.8	10.2	0.50									0.5	0.5		(Kaewmai *et al.*, 2013)
19	Biogas plant upgrading with bioreactor		7.5	5.8	-2.6	10.7	0.50									0.5	0.5		(Pattanapongchai, A. Limmeechokchai, 2011)

20	Pre heating fiber	Pre-heating fiber	0.1	0.1	-3.9	-3.7									0.5				(DEDE, 2007)
21	Wet scrubber	S_2O control for fiber combustion	0.5	0.4		0.9			0.9	0.65	0.74		0.85						(Ruitang and Gao, 2009)
22	Thermal incinerator	VOC control for fiber combustion	0.3	0.1		0.4					0.99	0.89	0.88						(EPA, 2003d)

Adapted from (Saswattecha *et al.*, 2016)

Appendix G

GAMS Script for Mill C's Case Study

variable
Totcost total cost for mitigation selected ;

binary variable
x1 mitigation option by EFB combustion
x2 mitigation option by EFB pellets production
x3 mitigation option by EFB composting plant
x4 mitigation option by Ethanol production
x5 mitigation option by Pellets production
x6 mitigation option by Composting plant
x7 mitigation option by Selective catalytic reduction
x8 mitigation option by Selective non catalytic reduction
x9 mitigation option by Low NOx burner
x10 mitigation option by Non thermal plasma
x11 mitigation option by Oil recovery from decanter
x12 mitigation option by Oil recovery from fiber
x13 mitigation option by Oil recovery from EFB
x14 mitigation option by Oil recovery from POME
x15 mitigation option by Cyclones
x16 mitigation option by Baghouse
x17 mitigation option of electrostatic precipitator
x18 mitigation option of biogas plant
x19 mitigation option of biogas plant upgrading with bioreactor
x20 mitigation option by Pre heating fiber
x21 mitigation option by Wet scrubber
x22 mitigation option by Thermal incinerator;

equation
eq1 objective function
eq2 standard requirement for ch4

```
eq3     standard requirement for so2
eq4     standard requirement for PM
eq5     standard requirement for EG
eq6     standard requirement for DIP
eq7     cluster of EFB treatment
eq8     cluster of NOx control for fiber combustion
eq9     cluster of Oil extraction improvement
eq10    cluster of PM control for fiber combustion
eq11    cluster of POME treatment
eq12    cluster of Pre-heating fiber
eq13    cluster of S2O control for fiber combustion
eq14    cluster of VOC control for fiber combustion
eq15;
eq1..   Totcost =e= 140.6*x1 - 9.8*x2 - 1.4*x3 + 27.2*x4 - 9.8*x5 - 1.4*x6 + 4*x7
        + 3*x8 + 1*x9 + 4.5*x10 - 4.2*x11 -7.6*x12 - 3.8*x13 - 3.3*x14 + 0.6*x15
        +  0.4*x16 + 1.7*x17 + 10.2*x18+ 10.7*x19 - 3.7*x20 + 0.9*x21 + 0.4*x22 ;
eq2..   0.09*0.5*x18 + 0.09*0.5*x19 - 0.09*0.005*x1 =g= 0.045;
eq3..   0.09*0.9*x21 =g= 0.009;
eq4..   0.09*0.85*x21 + 0.09*0.88*x22 + 0.09*0.8*x15 + 0.09*0.99*x16 +
        0.09*0.99*x17 =g=0.009;
eq5..   0.09*0.5*x18 + 0.09*0.5*19 =g=0.045;
eq6..   0.09*0.5*x18 + 0.09*0.5*x19 =g=0.045;
eq7..   x1 + x2 + x3 + x4 + x5 + x6 =l= 1;
eq8..   x7 + x8 + x9 + x10 =l= 1 ;
eq9..   x11 + x12 + x13 + x14 =l=1;
eq10..  x15 + x16 + x17 =l= 1;
eq11..  x18 + x19 =l=1;
eq12..  x20 =l=1;
eq13..  x21 =l=1;
eq14..  x22 =l=1;
eq15..  x2 + x3 + x4 + x5 + x6 + x7 + x8 + x9 + x10 + x11 + x12 + x13 + x14 +x20
=e= 0;
model process /all/;
solve process using MIP minimizing TotCost;
```

LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Jamaludin, N. F.**, Hashim, H., Muis, Z., Zakaria, Z. Y., Jusoh, M., Yunus, A., & Abdul Murad, S. M. (2018). A sustainability performance assessment framework for palm oil mills. Journal of Cleaner Production, 174, 1679 – 1693. https://doi.org/10.1016/j.jclepro.2017.11.028 . **(Q1, IF: 6.352)**

2. **Jamaludin, N. F.**, Hashim, H., Muis, Z. (2019). An Integrated Carbon Footprint Accounting and Sustainability Index for Palm Oil Mills. Journal of Cleaner Production, *225, 496 – 509* **(Q1, IF: 6.352)**

Indexed Journal

1. **Jamaludin, N. F.**, Hashim, H., Muis, Z. Ahamad, R (2016). Environmental index for palm oil mill. Chemical Engineering Transactions, 52, 1177-1182 **(Indexed by SCOPUS)**

2. **Jamaludin N.F.**, Hashim H., Muis Z.A., Ho W.S., 2017, Sustainability framwork for palm oil mill, Chemical Engineering Transactions, 56, 7-12 DOI:10.3303/CET175600 **(Indexed by SCOPUS)**