Journal of Cleaner Production 225 (2019) 496–509

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

An integrated carbon footprint accounting and sustainability index for palm oil mills

Nabila Farhana Jamaludin [a, b], Zarina Ab Muis [a, b, *], Haslenda Hashim [a, b]

[a] PROSPECT (Process Systems Engineering Centre), Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia
[b] School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia

ARTICLE INFO

Article history:
Received 25 July 2018
Received in revised form
26 March 2019
Accepted 28 March 2019
Available online 1 April 2019

Keywords:
Carbon accounting
Carbon footprint
Carbon footprint accounting
Sustainability assessment
Integrated assessment
Palm oil mill
Big data analysis

ABSTRACT

Palm oil industry has received criticism from various parties on the issue of sustainability and the greenhouse gases. Carbon footprint accounting are widely used as a metric of climate change impacts and the main focus of many sustainability policies among companies and authorities. However, carbon footprint accounting has limitation to represent sustainability as a whole and may resulting inaccurate selection of further mitigation. This paper evaluates sustainability and greenhouse gases simultaneously using an integrated palm oil mill carbon footprint accounting (POMCFA) and palm oil mill sustainability index (POMSI) method. The integration was performed via the adoption of data synchronization of the carbon footprint accounting and sustainability assessment. The analysis shows that highest carbon dioxide equivalent emission was contributed by palm oil mill effluent followed by diesel consumption and water consumption. In terms of sustainability scoring, the results show that the environmental aspect achieved the lowest scores compared to other aspects (social and economy). Weaknesses identified include diesel consumption, palm oil mill effluent and boiler emission. The assessment analysed in terms of carbon dioxide equivalent and sustainability scoring demonstrates its potential to provide comprehensive mitigation selection purposes.

1. Introduction

Malaysia, as the world's second leading palm oil producer after Indonesia, has a vast palm oil industry (Rashidi and Yusup, 2017). Malaysia contributed up to 17 MT of oil palm production in 2016. This value increased to 20 MT in 2017 (MPOB, 2018). Umar et al. (2017) indicated palm oil production is vital to Malaysia's economy as palm oil export revenue was found to increase by 5.1% from RM41.26 $\times$ 10^9 in 2015 to RM43.37 $\times$ 10^9 in 2017 (Din, 2017). The rapid development of the oil palm industry has resulted in negative consequences of sustainability, especially the impact on the environment due to land use change and greenhouse gases (GHGs) emission.

International organisations such as Intergovermental Panel on Climate Change (IPCC) and United Nations Framework Convention on Climate Change (UNFCCC) have proposed the accounting of GHGs to help companies measure the emission (Brander, 2016). This is in line with the vision of international conventions such as The Kyoto Protocol 1992, Bali Roadmap 2007, and Copenhagen Agreement 2009, which are committed to reducing emissions and implementing action plans (Gao et al., 2014) to achieve a sustainable environment. A Working Group on Greenhouse Gases for the palm oil industry has been established by Roundtable on Sustainable Palm Oil (RSPO) to achieve a similar vision (RSPO, 2013). With increased attention on climate change, demand for GHGs emission information of palm oil products has increased, in relation to the increasing palm oil demand and pressure from land-use change, which have resulted in additional GHGs emissions. Klaarenbeeksingel (2009) reported that RSPO (2013) re-enacted its Principles & Criteria, considering that palm oil production can only be claimed sustainable when consideration has been given to mitigation of GHGs emission.

Some of the carbon account accounting terminology that are often used at the national scale are carbon footprint (Stechemesser and Guenther, 2012; Bowen and Wittneben, 2011; Ascui and Lovell, 2011), and carbon footprint accounting (Dong et al., 2013; Schmidt, 2009). In this study, terms carbon footprint accounting will be used throughout the article. Rosen (2016) reported that the methods and results for carbon footprint accounting can vary, but its prevalence has prompted more companies to set goals for reducing their GHGs

* Corresponding author. School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia.
E-mail address: zarinamuis@cheme.utm.my (Z.A. Muis).

https://doi.org/10.1016/j.jclepro.2019.03.312

emissions. Wright et al. (2014) contested carbon footprint accounting is a measure of the total amount of carbon dioxide (CO_2) and methane (CH_4) emissions of a population, system, premises or activity. A significant emissions proportion can be measured by including only two most prominent GHGs, CO_2 and CH_4 for straightforward, cost effective assessment and practical to be applied by all types of organisations. He also proposed inclusion of all GHGs gases for comprehensive measure of carbon footprint accounting. Fenner et al., (2018) stated there are three alternatives to assess carbon footprint accounting which are considered CO_2 alone, Kyoto Protocol six gases (CO_2, CH_4, N_2O, HFCs, PFCs, and SF6) and multiple GHGs gases by the IPCC framework. It considers all relevant sources, sinks, and storage within the boundary of the population, system, or activity for the calculation (Bowen and Wittneben, 2011). However all of them agreed a single metric that comprises all GHGs is commonly represented as carbon dioxide equivalent (CO_2e).

Carbon footprint accounting is important to help industries evaluate GHGs emission and to propose a necessary improvement to processes. For instance, Coca-Cola aims to reduce its emissions by one-fourth by 2020, the same year in which Unilever, one of the largest consumer goods companies in the world, aims to cut emissions in half (Rosen, 2016). Although carbon footprint accounting has been widely used as a metric to measure climate change impact, the approach is not sufficiently comprehensive to address sustainability concerns since the focus on carbon footprint accounting method only shows the reduction in GHG parameter but the expense in other sustainability impacts somehow have been overlooked (Laurent et al., 2012). The focus of carbon footprint accounting could bring about the risk of problem shifting i.e. when reductions in GHGs emissions are obtained at the expense of an increase in other sustainability impacts (Grafakos et al., 2016).

The sustainability assessment is essential to provide a comprehensive analysis of industry performance. Malaysian palm oil producers such as FELDA need to apply the sustainability assessment certification and meet the criteria to enter the European market. This sustainability certification will serve as proof to the giant multinational consumers. Multinational companies such as Starbucks and Unilever are committed to use only 100% sustainable certified palm oil for its products by 2015 (Mazzoni, 2014) but most of the existing sustainability indices do not include carbon footprint accounting as part of the assessment. The palm oil industry needs to conduct separate assessment for the GHGs emission and sustainability assessment. In the absence of systematic tool, different reports have to be submitted to different authorities for the endorsement of sustainability indicators. Such practice places a heavy toll on the palm oil industry and resulting in a higher cost and corporate responsibility. Some of the existing assessments with their limitations are summarised in Table 1.

As shown in Table 1, none of the previous works had introduced an integrated framework to quantify both sustainability and GHGs emission. RSPO is the closest global assessment for sustainability practices and GHGs emission using a qualitative approach. The National Corporate Greenhouse Gas Reporting Programme for Malaysia, known as MYCarbon, provides a reporting programme with the aim of ensuring consistency and comparability of data for GHGs emission only. Taking these factors into account, the framework is developed by integrating carbon footprint accounting (POMCFA) and Palm Oil Mill Sustainability Index (POMSI) with respect to standards, regulations, or policies by Jamaludin et al. (2018).

This paper presents the development of a palm oil mill assessment framework that integrates both the sustainability index and carbon footprint accounting. The other phases of the framework identify weak indicators and provide a comprehensive platform for appropriate mitigation step decision making. This tool is expected to aid the industry to quantify both the sustainability and GHGs emission simultaneously. The tool also conducts control profiling and take necessary action to improve the weaknesses in any palm oil mill premises. Section 2 presents a general methodology integrating Palm Oil Mill Carbon Footprint Accounting (POMCFA) with Palm Oil Mill Sustainability Index (POMSI). In section 3, a case study of evaluating the local palm oil mills using the methodology in section 2 is presented and discussed.

2. Methodology

This section presents a detailed method for the development of an integrated sustainability assessment framework for the palm oil mill industry by integrating POMCFA and the Palm Oil Mill Sustainability Index (POMSI). As shown in Fig. 1, this integrated framework is divided into four main parts: 1) the development of Palm Oil Mill Carbon Footprint Accounting (POMCFA); 2) POMCFA analysis and improvements; 3) development of the Palm Oil Mill Sustainability Index (POMSI); 4) POMSI analysis and improvements; and 5) Integrated improvement plan for POMCFA and POMSI. Each part is discussed in more detail in the next section. The results for Parts 3 and 4 have previously been reported by Jamaludin et al. (2018) and will not be discussed in detail. The focus of this study is to introduce the integrated part of the framework as an extension to the previous work.

2.1. Part 1: development of palm oil mill carbon footprint accounting (POMCFA) integrated with sustainability index

2.1.1. Step 1: plant familiarisation

POMCFA was developed to provide a quantitative and effective approach for presenting the complex sustainability data of a palm oil mill. This step gives a brief introduction to the palm oil mill industry and an overview of the processes used. This information is important to understand the process and identify the mill component, operational data to be used in the next step. Having this knowledge will help the selection of relevant indicators, parameters and aspects for this framework.

2.1.2. Step 2: identifies indicators, parameters of the GHGs source

POMCFA aims to assess the GHGs emission of palm oil mill with respect to carbon dioxide equivalent (CO_2e) unit. The assessment consists of three layers, which are indicators, parameters, and aspects. The indicators are selected based on relevance, performance orientation, transparency, data quality, data sustainability, and data custodian (Ahamad et al., 2015). The selection of indicators is based on current GHG reporting such as MYCarbon. The final decision is taken through a series of engagements with subject experts of palm oil mills, subject to data availability. Every parameter and indicator unit is based on per 1 MT fresh fruit bunch (FFB) production. The emission result of POMCFA is also based on the same unit. This is in parallel with the statement of Klaarenbeeksingel (2009) in that emissions related to operations at the plantation and the mill are generally applied as a per t CPO or FFB basis. A list of parameters and indicators used in this study is given in Table 2.

2.1.3. Step 3: GHGs mapping

With the establishment of the POMCFA database, GHGs mapping is conducted to identify GHGs emission sources by each stream and operation unit. The stream is represented by symbols S1, S2, etc., as outlined in Table 3.

Table 1
Recent studies on sustainability assessment and carbon footprint accounting assessment.

Author(s)	Objective	Application	Limitation
Kaewmai et al. (2012)	To develop a methodology for calculating GHGs emissions of palm oil mills in Thailand.	Palm oil mill	Only focused on the GHGs emissions calculation methodology.
Hashim et al. (2014)	To develop a new systematic tool known as the Green Industrial Performance Scorecard (GIPS) to assess the sustainability of the palm oil industry.	Palm oil industry	This tool assesses palm oil industry performance based on the environmental aspect. A carbon footprint accounting method was not included; the real figure of emission cannot be calculated.
Ahamad et al. (2015)	To develop an Environmental Performance Index in Malaysia at the State level.	State/Country	The method can only assess the environmental performance of the country but the real figure of emission cannot be calculated since carbon footprint accounting is not included.
Chand et al. (2015)	To develop an integrated sustainability index for small dairy farm holders in Rajasthan, India.	Dairy farm	The framework focused on the development of a sustainability assessment method for a multi-attribute farm level where carbon footprint accounting is not included.
Feil et al. (2015)	To select and identify the indicators for quick measurement of sustainability in small furniture industries.	Furniture Industry	The framework only focused on the sustainability aspect where carbon footprint accounting is not included.
Hashim et al. (2015)	To develop an Integrated Carbon Accounting and Mitigation		
Framework for greening the industry.	Nickel Electroplating Industry	The framework only focused on carbon footprint accounting development with extended integration of mitigation steps. However, sustainability assessment is not included.	
Jasinki et al. (2015)	To develop a Sustainability Assessment Model (SAM) that consolidates all sustainability aspects into a single method for the automobile industry.	Automobile	The framework focused on integrating different types of sustainability aspects into a single method, but the carbon footprint accounting method was not included.
Tan et al. (2015)	To develop a holistic low-carbon city indicator framework for sustainable development.	Low-carbon city	The framework focused on assessing a low-carbon city but did not include the assessment of carbon footprint accounting.
Geibler et al. (2016)	To integrate quantitative material input and semi-quantitative decisions regarding environmental weaknesses in the single-serve coffee value chain.	Coffee value chain	The method introduced an integrated quantitative and semi-quantitative method limited to assessing the environmental aspect only.
Grafakos et al. (2016)	To develop an integrated sustainability and resilience framework of indicators for the assessment of low carbon energy technologies at the local level.	Energy technologies	The framework only focused on the selection of criteria and indicators of sustainability and resilience for energy technologies.
Rivera and Reyes-Carillo (2016)	To develop a life cycle assessment framework for the environmental evaluation and decision-making of automobile paint shops.	Automobile paint shops	Assessment limited to environmental aspect only.
Suttayakul et al. (2016)	To conduct a water footprint assessment of oil palm plantations and palm oil mills in Thailand.	Palm oil industry	The methodology limited to water impact on the industry.
Ahmad et al. (2015)	To develop a systematic framework for carbon capture process	Carbon capture	The framework is using a model-based approach to design the optimal solvent for carbon capture. The analysis from this study overlooked on sustainability aspect and only emphasize on carbon footprint accounting parameter.
Lim and Biswas (2017)	To develop triple bottom line indicators for sustainability assessment framework of Malaysia palm oil industry	Palm oil industry	The framework is only focused on sustainability indices and not included carbon footprint accounting in the assessment. The assessment also neglected authorities standard value as a benchmark.
Musikavong and Gheewala (2017)	To assess ecological footprints and develop a methodology for reducing the ecological footprint of the rubber and palm oil mill industry in Thailand.	Palm oil mill	The methodology only focused on the ecological aspect without indicating the real figure of carbon emission.
Sahimi et al. (2017)	To develop Sustainability Assessment Framework in Hydropower sector using a mathematical modelling approach	Hydropower sector	The framework used a mathematical model to quantify the sustainability index. Carbon footprint accounting is not included in the framework.
Amin and Talebian-Kiakalaieh (2018)	Reduction of CO_2 emission using an INCAM model for biomass power plants in Malaysia for the year 2016.	Biomass power plants	This study applied an INCAM model framework for biomass power plants, which only focused on carbon footprint accounting.

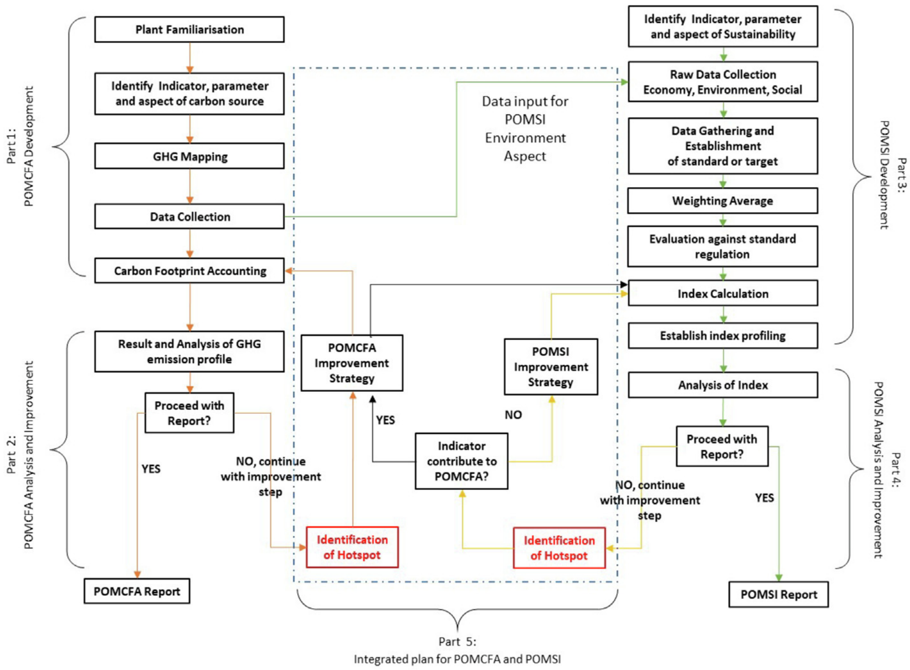

Fig. 1. Framework integrating the Carbon Footprint Accounting andPalm Oil Mill Sustainability Index.

Table 2
List of parameters and indicators

Aspect	Parameter, p	Indicator, i	Unit
Environment	Water Consumption	Use of freshwater	m^3
	Air Quality (Boiler Emission)	Dust Concentration @ 12% CO_2 +PM_{10} +$PM_{2.5}$	g/Nm^3
		Sulphuric Acid Mist	g/Nm^3
		Sulphur Dioxide SO_2	g/Nm^3
	Wastewater	Mixed Raw Effluent/POME	t
	Diesel Consumption	Diesel used for Process	L
		Diesel used for Transport	L

2.1.4. Step 4: collecting monthly consumption or generation of data for each mapped stream

Based on the mapping, the monthly consumption or generation of parameters will be identified for each parameter. The indicator for each stream is also determined. The data will also be used as input into the POMSI environment. This will reduce the process of entering data and any redundancy can be avoided.

2.1.5. Step 5: GHGs accounting

The emission factor must first be determined. Based on the GHG parameter, the emission factor will be obtained from related GHGs reporting authorities such as MYCarbon. An aggregate factor for GHGs gases is provided in kg or t of CO_2 equivalent (CO_2e) emissions referred as carbon dioxide equivalent emission factor, $EFCO_2e$. The $EFCO_2e$ obtained comprises most GHGs gases which in line with Kyoto Protocol guidelines (NRE and UNDP, 2014; DEFRA, 2018). The $EFCO_2e$ unit was also revised so it would be standardised with the carbon footprint accounting parameter unit for the comparing orders of magnitude purposes.

In the next step, emission calculation is conducted by multiplying $EFCO_2e$ with the monthly consumption or generation (D) indicator in order to quantify the amount of CO_2e emitted for each consumption (aCO_2e) as per Eq. (1). The value is summed up by the indicator, i, parameter, p, operation unit, uo, or stream, s to get total CO_2e, tCO_2e for each group of indicator, parameter, unit operation and stream using Eqs. (2)–(5).

$$aCO_2e = EFCO_2e \times D \tag{1}$$

Table 3
Stream division for each operation unit

Operation Unit, uo	Stream, s	Operation Unit, uo	Stream, s	Operation Unit, uo	Stream, s	Operation Unit, uo	Stream, s
Sterilisation	S1	Separation of kernel and shell from nut	S11	Fibre sent OE	S11n	Removal of sludge and solids from oil	S14
	S2		S11a	Deoiled fiber	S11p		S14a
	S3		S11b	Dry shell for boiler fuel	S11q		S14b
	S4		S11c	Superheated steam	S11r		S14c
Stripping	S5		S11d	Steam for process heating	S11s		S14d
	S6		S11e	Steam for driving turbine	S11t		S14e
Digestion	S7		S11f	Steam for process heating	S11u	Clarified oil	S15
Recycle	S8		S11g	Removal of fibrous tailings	S12		S16
Digestion	S9		S11h	Crude oil tank	S13	Purified oil	S17
Pressing	S10		S11i			Removal of water from oil	S18
Dilution	S10a		S11j				
	S10b		S11k				
			S11L				
			S11m				

$$tCO_2e\ for\ indicator = \sum_i aCO2e \quad (2)$$

$$tCO_2e\ for\ parameter = \sum_p aCO2e \quad (3)$$

$$tCO_2e\ for\ unit\ operation = \sum_{uo} aCO2e \quad (4)$$

$$tCO_2e\ for\ stream = \sum_s aCO2e \quad (5)$$

The emission is analysed by GHG emission profile in percentage (%). The result was analysed based on indicator, parameter, operation unit, and stream. To calculate the GHG emission profile (%) for indicator, the tCO_2e for indicator was divided with overall total CO_2e ($otCO_2e$) and multiplied by 100. To calculate the GHG emission profile (%) for parameter, the tCO_2e of parameter was divided with $otCO_2e$ and multiplied by 100. To calculate the GHG emission profile for stream and unit operation, the tCO_2e of each was divided by the $otCO_2e$ and multiplied by 100. Eq. (6) calculates the GHG emission profile, which is applicable to all variables (indicator, parameter, operation unit, and stream).

$$\text{GHG emission profile}(\%)(\mathrm{i, p, u, s}) = \frac{tCO_2e(i, p, uo, s)}{otCO_2e} \times 100 \quad (6)$$

2.2. Part 2: palm oil mill carbon footprint accounting analysis and improvement

2.2.1. Step 6: GHG emission profile result and analysis

Based on the calculation, the GHG emission profile (%) is developed to assess GHGs level. The result was analysed based on indicator, parameter, stream, and operation unit. The result will also be analysed together with the POMSI result to formulate further improvement strategies.

2.2.2. Step 7: report generation

A report is generated as the assessment result for the purpose of documentation, database, etc.

2.2.3. Step 8: identifying hotspot

Based on the result and analysis, the hotspot (the part contributing to the most GHGs emission) will be identified and appropriate improvements proposed. The GHG emissions score is recalculated to simulate the feasibility of improvements and to show the significance of GHG emissions reduction after application of the improvements. Once the selected improvement has been chosen, an improvement report can be generated based on the latest calculation. Even so, this can only consider GHG emissions reduction strategies and neglects some aspects such as the economic aspect and sustainability is not portrayed as a whole. The integration method for a more holistic analysis is discussed in Part 5 of Section 2.5.

2.3. Part 3: development of the palm oil mill sustainability index (POMSI)

As discussed by Jamaludin et al. (2018), the development of a sustainability index for palm oil mills requires ten steps: 1) identifying the indicator, parameter, and aspect of palm oil mill sustainability; 2) raw data collection; 3) data gathering and establishment of target; 4) determination of weighting average of the parameter; 5) evaluation against standard regulation; and 6) index calculation. Steps 7–10 are outlined in Section 2.4.

2.4. Part 4: palm oil mill sustainability index analysis and improvement

The steps continue to step 7) establish index profiling, 8) analysis of index, 9) report generation, and 10) identification of hotspot. Based on the sustainability index profile and analysis in step 8, the areas of weaknesses (hotspots) are identified and improvements to the hotspot are proposed. The sustainability performance score will be recalculated to evaluate the effectiveness of the proposed improvement. Still, this assessment is not comprehensive enough, as it lacks a GHGs emission analysis and carbon footprint accounting. The integration of POMCFA and POMSI is needed as a more holistic assessment.

2.5. Part 5: integrated mitigation of POMCFA and POMSI

To address the limitations as discussed above, an integrated system of carbon footprint accounting and sustainability assessments is created. The system combines data input from POMCFA and POMSI (environment) into one data entry and generates results for both assessments simultaneously. The integration can avoid data redundancy and deliver a fair judgement for the mitigation selection. For the mitigation part, if any of the hotspots need to be improved, a recalculation will be done as per explained in section 2.1 step 5 for POMCFA and section 2.3 step 5 for POMSI to fulfill the carbon footprint accounting and sustainability criteria and to justify the effectiveness of the improvement as a whole, as shown in Fig. 2.

3. Case study

This study was conducted in a palm oil mill in Malaysia in 2015. The crude palm oil (CPO) production capacity of the mill is 1 t of fresh fruit bunches (FFB). The main products produced by this company are CPO and palm kernel (CKPO).

3.1. Part 1: POMCFA development

A case study was conducted to apply the framework integrating Carbon Footprint Accounting (POMCFA) and Palm Oil Mill Sustainability Index (POMSI).

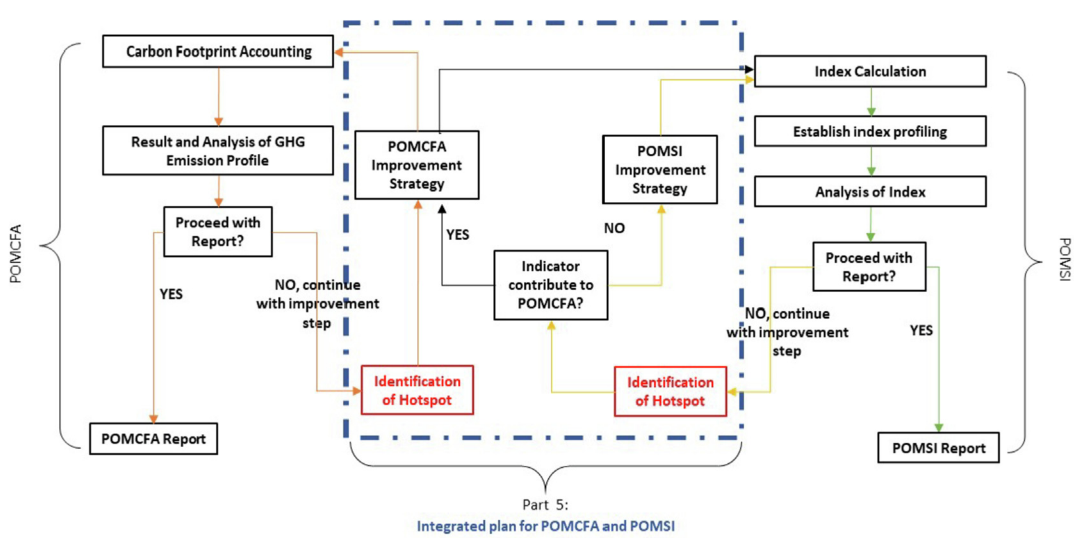

Fig. 2. Integrated POMCFA and POMSI.

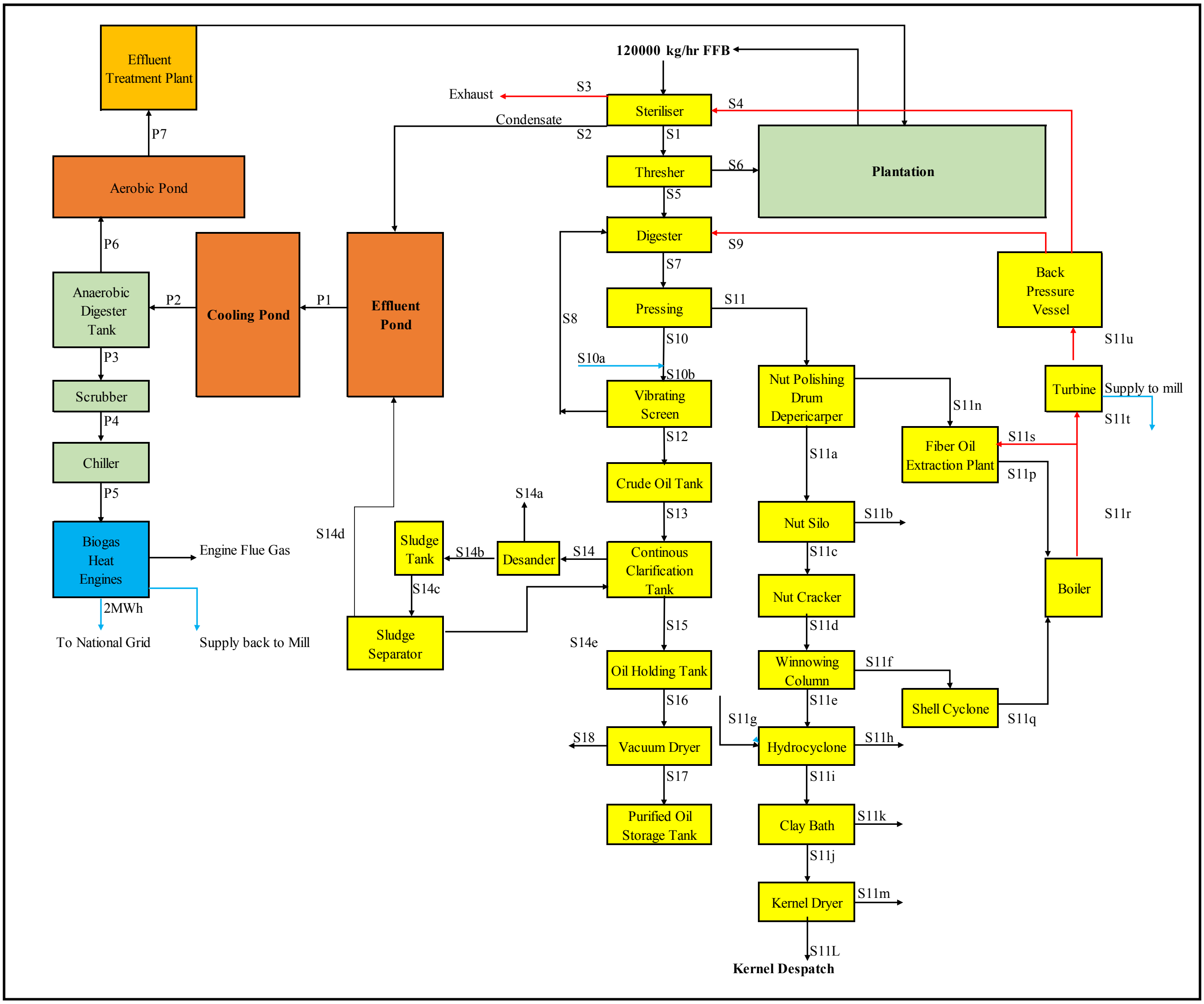

Fig. 3. Palm oil mill flow chart.

3.1.1. Step 1: plant familiarisation

Fig. 2 shows the process flow diagram of the palm oil mill industry. The processes in the palm oil mill aim to get crude oil from palm oil. There are five main processes in this operation, which are: 1) sterilization; 2) threshing; 3) digestion; 4) pressing; and 5) clarification with stream division, as shown in Table 3. The subprocess for the main process varies from one industry to another. Fig. 3 shows the palm oil mill flow chart used in this study.

3.1.2. Step 2: identify indicators, parameters, and aspect of the carbon source

Based on Fig. 3, four carbon footprint accounting parameters are identified, which are the water consumption for the process, boiler emission, wastewater generated from palm oil mill processes, and diesel consumption of the mill, as shown Table 2. Every parameter and indicator unit is based on the processing of 1 t fresh fruit bunch (FFB) to provide the emission result using POMCFA. This is in parallel with the statement of Klaarenbeeksingel (2009) where the emissions related to the operations in the plantation and mill are calculated per t of CPO or FFB.

3.1.3. Step 3: carbon mapping

The unit operation, uo and stream, s based on Fig. 3 are listed in Table 3 for GHGs mapping purposes. This step is taken to maps GHGs utilizing relating palm oil mill operation based on indicator, parameter, stream and unit operation. GHG emissions is identified from the dilution unit operation, in the streams of S10b, S12, S13, S14, S14b and S14c, due to freshwater activity (indicator) where water consumption parameter are mapped accordingly based on the information. The full GHGs mapping can be referred to Table 4.

3.1.4. Step 4: monthly consumption or generation of data for each stream

Table 4 shows GHGs mapping of the particular stream. Data of the mapped indicators are collected to develop a database as shown in Table 5.

3.1.5. Step 5: carbon footprint accounting

To obtained emissions for each consumption, aCO_2e, the monthly indicator data, D as shown in Table 5 is multiplied with $EFCO_2e$ as Eq. (1). Then the value is summed up to get tCO_2e for

Table 4
GHGs Mapping

Parameter	Indicator	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S10a	S10b	S11	S11a	S11b	S11c	S11d	S11e	S11f	S11g	S11h	S11i	S11j	S11k	S11L	S11m	S11n	S11p	S11q	S11r	S11s	S11t	S11u	S12	S13	S14	S14a	S14b	S14c	S14d	S14e	S15	S16	S17	S18
Water Consumption	Use of fresh water	m3/Mt												X																						X	X	X		X	X						
Air Quality (Boiler Emission)	Dust Concentration @ 12% CO2 +PM10 +PM2.5	g/Nm³			X																																										
	Sulfuric Acid Mist	g/Nm³			X																																										
	Sulfur Dioxide SO_2	g/Nm³			X																																										
Waste water	Mixed Raw Effluent /POME	Mt/Mt		X													X						X	X	X	X	X	X														X					
Diesel Consumption	Diesel used for Process	L/Mt																												X																	
	Diesel used for Transport	L/Mt																												X																	

Table 5
Monthly Consumption or Generation data, D

Unit Operation, uo					Sterilisation		Dilution	Seperation of kernel and shell from nut							Deoiled fibre	Removal of fibrous tailings	Crude oil tank	Removal of sludge and solids from oil			
					Stream, s																
Aspect	Parameter, p	Symbol	Indicator, i	Unit	S2	S3	S10b	S11b	S11h	S11i	S11j	S11k	S11L	S11m	S11p	S12	S13	S14	S14b	S14c	S14d
Environment	Water Consumption	nWC	Use of fresh water	m³/Mt			0.16									0.16	0.16	0.16	0.16	0.16	
	Air Quality (Boiler Emission)	nAQ	Dust Concentration @ 12% CO_2 +PM_{10} +$PM_{2.5}$	g/Nm³		0.01															
			Sulphuric Acid Mist	g/Nm³		0.0001															
			Sulphur Dioxide SO_2	g/Nm³		0.0008															
	Wastewater	nWAS	Mixed Raw Effluent /POME	Mt/Mt	0.19			0.012	0.032	0.0096	0.0070	0.0025	7.65E-05	0.0069							0.26
	Diesel Consumption	nDIC	Diesel used for Process	L/Mt											0.3						
			Diesel used for Transport	L/Mt											0.21						

Table 6
Emission Factor of each indicator.

Indicator	Carbon Dioxide Equivalent Emission Factor ($EFCO_2e$)	References
Use of freshwater	0.34 kg/m³	DEFRA (2018)
Dust Concentration @ 12% CO_2 +PM_{10} +$PM_{2.5}$	0.77 g/Nm³	NRE and UNDP (2014)
Sulphur Dioxide, SO_2	1.84 g/Nm³	NRE and UNDP (2014)
Mixed Raw Effluent/POME	17.95 kg/t	NRE and UNDP (2014)
Diesel used for Process	3.13 kg/L	NRE and UNDP (2014)
Diesel used for transport	3.13 kg/L	NRE and UNDP (2014)

stream and unit operation (Table 7) and tCO_2e for indicators and parameters, as shown in Table 8. Emission Factor, $EFCO_2e$ is used for the calculation of GHGs emission, the value is presented in Table 6. The results and analysis from this calculation are presented in Part 2.

3.2. Part 2: palm oil mill carbon footprint accounting analysis and improvement

3.2.1. Step 6: result and analysis of carbon footprint accounting

The emission is analysed using GHG emission profile (%). The result was analysed based on the indicator, parameter, stream, and operation unit as described in Tables 2 and 3. Based on the calculation in Tables 7 and 8, the $otCO_2e$ is 11.26 kg/t of FFB.

As shown in Table 8, 9.33 kg emission of Mill A was contributed by wastewater generation (82.88%) due to the high generation of palm oil mill effluent (POME), as shown in Fig. 4 and Fig. 5. Based on GHG emission profile in Fig. 6, streams S2, S11b, S11h, S11i, S11j, S11k, S11l, S11m and S14d was found as the POME stream. Unit operations involved are sterilization, kernel and shell seperator from nut, and sludge and solids remover from oil unit as shown in Fig. 7. The second highest emission contributor is diesel consumption with 1.6 kg CO_2e produced, the amount is attributed to the process (0.94 kg CO2e) and transportation (0.66 kg CO2e. This emission represented 14.17% of the total emission based on Fig. 4, namely process (8.34%) and transportation (5.84%) (Fig. 5). The diesel consumption for the process and transportation are both located in S11p stream at deoiled fibre unit. The least contributor of

Table 7
Total monthly CO_2e for each stream and operation unit and GHG emission profile

Unit Operation, uo	Sterilisation		Dilution	Seperation of kernel and shell from nut							Deoiled fibre	Removal of fibrous tailings	Crude oil tank	Removal of sludge and solids from oil			
	Stream, s																
	S2	S3	S10b	S11b	S11h	S11i	S11j	S11k	S11L	S11m	S11p	S12	S13	S14	S14b	S14c	S14d
tCo_2e emission for each stream (kg)	3.37	0.0092	0.054	0.21	0.57	0.17	0.13	0.046	0.0014	0.12	1.60	0.054	0.054	0.054	0.054	0.054	4.71
GHG emission profile	29.94	0.081	0.48	1.84	5.08	1.52	1.12	0.41	0.01	1.10	14.17	0.48	0.48	0.48	0.48	0.48	41.85
tCo_2e for each operation unit (kg)	3.34		0.05	1.25							1.6	0.05	0.05	4.87			
GHG emission profile (%)	30.02		0.48	11.08							14.2	0.48	0.48	43.28			

Table 8
Total CO_2e emission for indicator and parameter and GHG emission profile (%)

Aspect	**Parameter, p**	**Indicator, i**	**Unit**
Environment	Water Consumption	Use of freshwater	m^3
	Air Quality (Boiler Emission)	Dust Concentration @ 12% CO_2 +PM_{10} +$PM_{2.5}$	g/Nm^3
		Sulphuric Acid Mist	g/Nm^3
		Sulphur Dioxide SO_2	g/Nm^3
	Wastewater	Mixed Raw Effluent/POME	t
	Diesel Consumption	Diesel used for Process	L
		Diesel used for Transport	L

the overall emission is boiler emission (0.081%, 0.0092 kg CO2e). Stream S3 in strerilisation unit required less attention compared to the POME and diesel consumption stream. To reduce these emissions at sterilization, deoiled fiber and sludge and solids remover and S14d, improvement can be done to specific streams with high emissions (S2, S11p and S14d) as shown in Table 6 and Fig. 6. These streams are diesel consumption stream and wastewater stream. The operation units that require improvement are sterilization, removal of sludge and solids from the oil stream and deoiled fibre unit as shown in Fig. 7.

The basis used is per t of FFB processed.

3.2.2. Step 7: report generation

Based on the analyses and results as shown in Step 1 through 6, a full report can be generated where identification of hotspots can be performed and necessary improvements be applied.

3.2.3. Step 8: identifying hotspot of POMCFA

The emission of Mill A was significantly contributed by wastewater generation (82.88%) due to the high generation of POME, as shown in Figs. 4 and 5. As indicated in Fig. 6, the high emission streams are S14d, S2, and S11p. The operation units that need to be improved are sterilization, removal of sludge and solids from the oil stream and deoiled fibre unit (Fig. 7). The second highest identified hotspot (a phase that contributes to highest emission) is diesel consumption, specifically for transport usage (Fig. 5). Referring to Fig. 6, stream S11p (deoiled fiber unit) could be improved. Therefore, the improvement method was integrated with POMSI framework (part 3 and 4) as discussed in Part 5 under Section 3.5. This integrated approach only consider GHGs emission reduction strategies and neglects some aspects such as the economic aspect, thus sustainability is not portrayed as a whole.

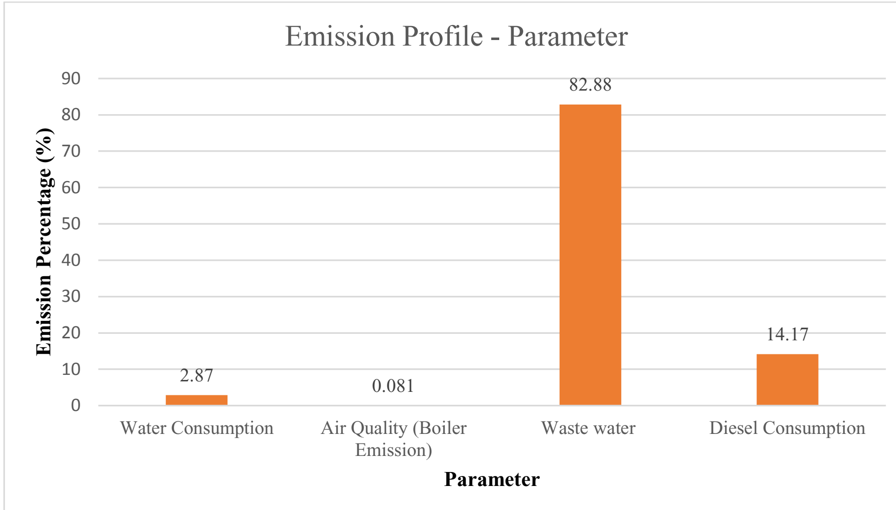

Fig. 4. Emission profile - parameter (%).

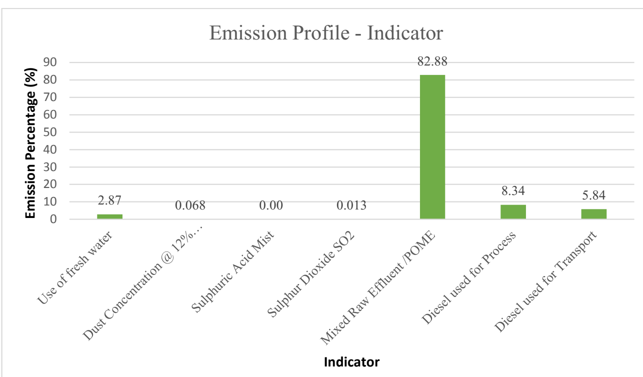

Fig. 5. Emission profile - indicator (%).

3.3. Part 3 and part 4: POMSI results and analysis

Based on subtopic 2.3 and 2.4, the result generated from the POMSI is shown in Fig. 8. This section highlights the sustainable performance for the assessed mill (Mill A) based on aspect, parameter, and indicator. Fig. 8 indicates that the environmental aspect achieved low scores as compared to the other aspects (social and economic). The low performance was due to the high consumption of diesel for transportation in Mill A. According to Jamaludin et al. (2018). Long operating hours was the key factor affecting the high usage of diesel in Mill A due to the long duration of vehicle usage and large capacity of Mill A to handle the transportation of FFB.

3.4. Part 5: integrated mitigation of POMCFA and POMSI

Based on the result and analysis of the POMCFA and POMSI assessment, the hotspot to be improved is diesel consumption for transportation. The mitigation proposed to replace the diesel with natural gas instead as shown in Table 9. Theoretically, the implementation of mitigation showed a positive sign as the recalculation of POMCFA Table 10 has shown the decline of the overall total emission from 11.26 kg-CO_2e to 10.61 kg-CO_2e where the diesel consumption of transportation reduced from 0.66 kg-CO_2e to 0.0066 kg-CO_2e. The proposed improvement reduced the consumption of diesel from 0.21 L/t to 0.002 L/t (Table 10) and based on POMSI evaluation, proximity to target (PTT) score of the environmental score has increased from 0 to 100%.Thus, increased total sustainability score from 92% to 95.5% as shown in Table 10.

Based on the reassessment of the environmental score, the mitigation step has shown a positive sign. Yet, the economic aspect as shown in Table 10 the cost increased from 46.94 RM/t to 50 RM/t where affecting the decreased of economic score from 100% to 90%. These results justify the significance of the selection of the mitigation plan. The decision would vary depending on the objective to achieve, if the only concern for the industry is environmental aspect then this improvement may be considered for implementation. If the industry concern considers economic aspect or both aspects, this mitigation does not meet the requirement and another mitigation option would be proposed. The re-assessment has considered GHG and sustainability aspects to comprehensively justify the effectiveness of mitigations. This integrated method demonstrated a more comprehensive analysis and decision tool for selecting the options to improve any identified weaknesses or hotspots for emissions.

4. Conclusions

A systematic methodology for carbon footprint accounting was developed based on indicators, parameters, stream, unit operation. The results were further integrated with palm oil mill sustainability index (POMSI). An integrated method was applied to solve the limitations of each assessment, where the objective was to avoid data redundancy and provide a comprehensive platform for the carbon footprint accounting and to improve the decision making. Application of this method revealed that the mitigation proposed can reduce 99% emission of diesel consumption for transportation from 0.66 kg-CO_2e to only 0.0066 kg-CO_2e. Its overall total emission has decreased for 6% from 11.26 kg-CO_2e to 10.61 kg-CO_2e. PTT score of environment aspect also shows positive changes 0%–100% score which lead to improved index score from 92% to 95.5%. In terms of economy aspect, the PTT score slightly dropped from 100% to 90% score. This indicate the mitigation proposed is effective to treat the environment's parameter weaknesses but relatively increase some cost to the industry. This factor would play big role in determining industries decision for optimal mitigation selection. Our study may serve as a preliminary study for helping the

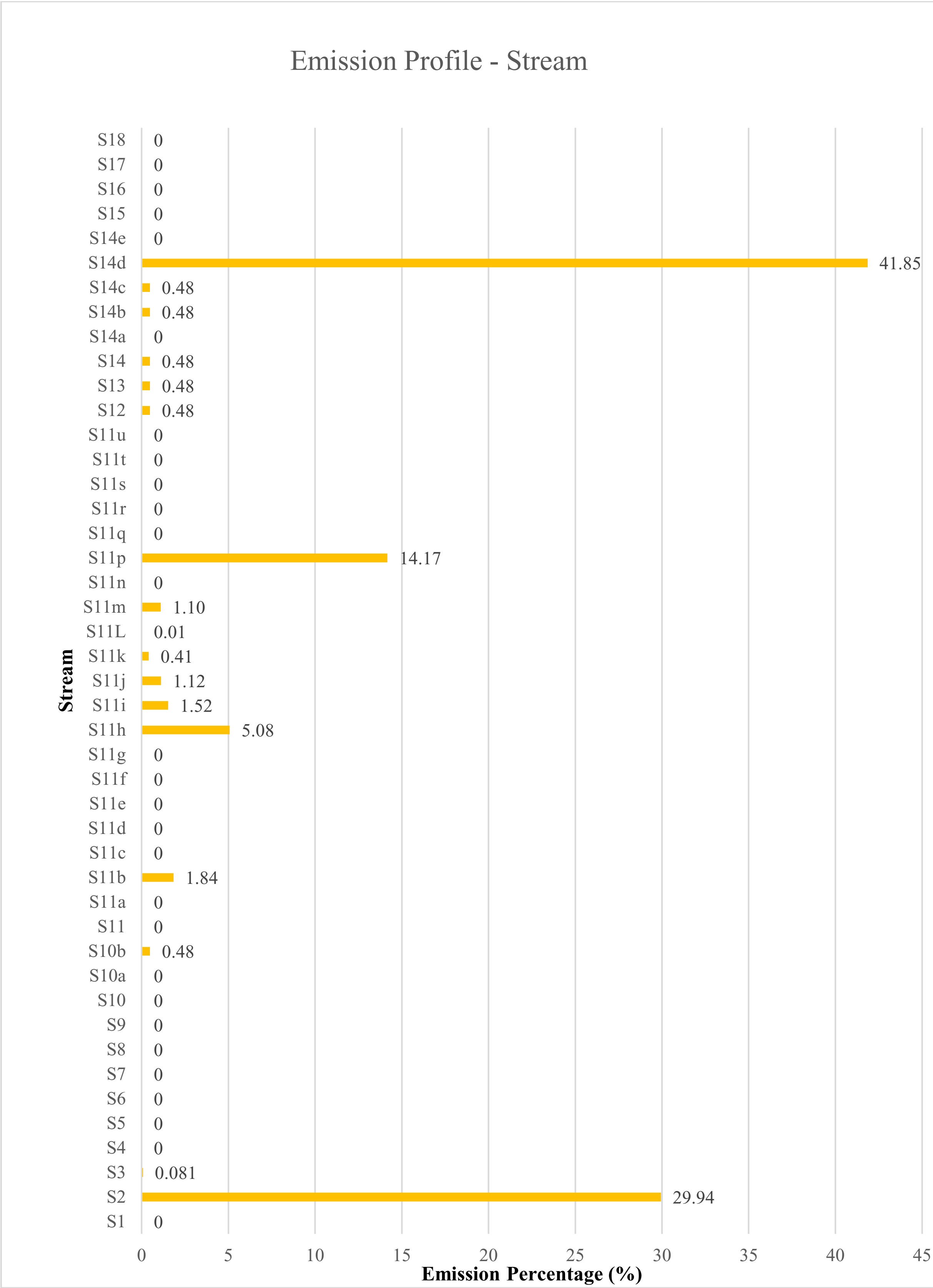

Fig. 6. GHG emission profile - stream.

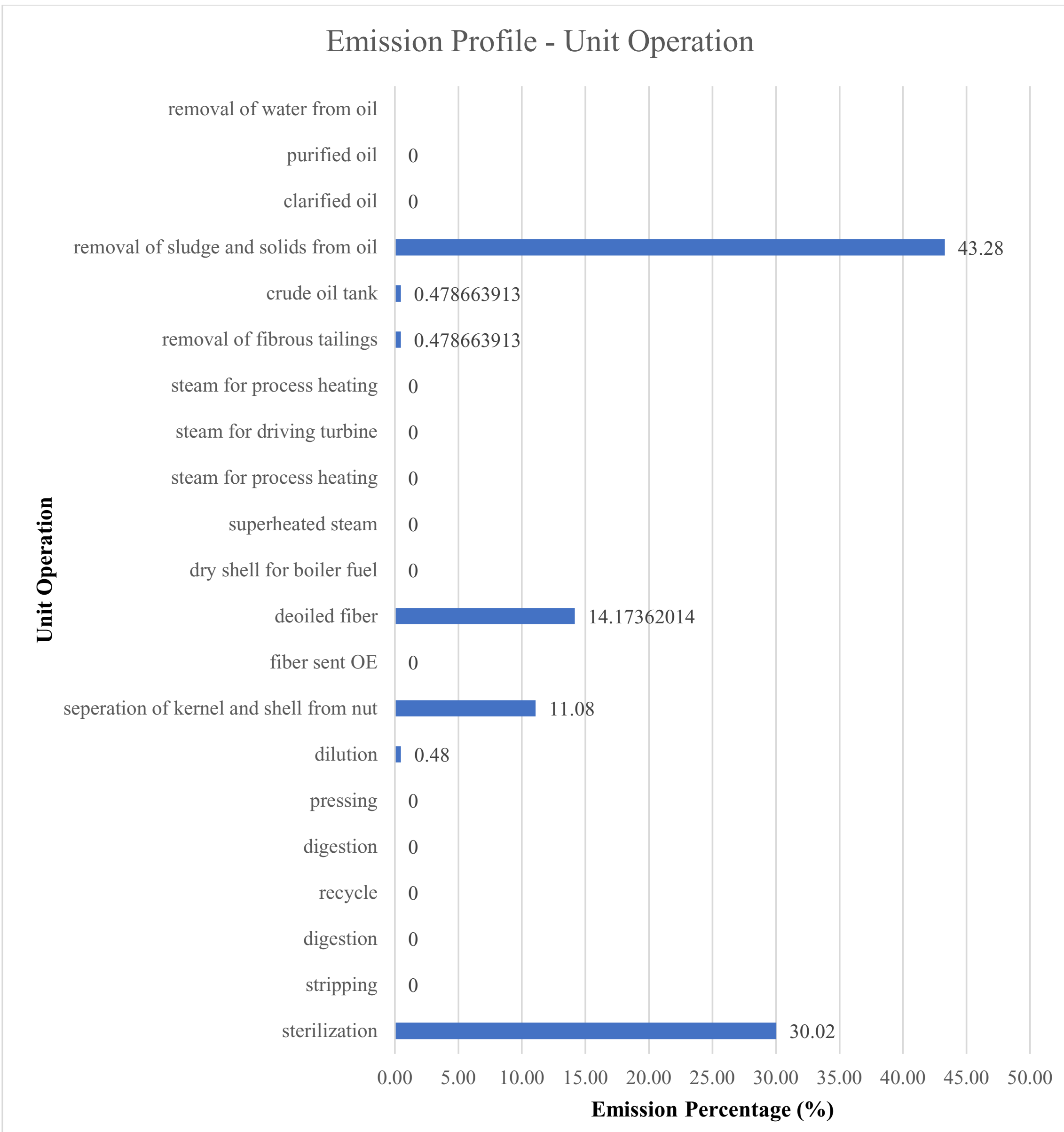

Fig. 7. GHG emission profile - unit operation.

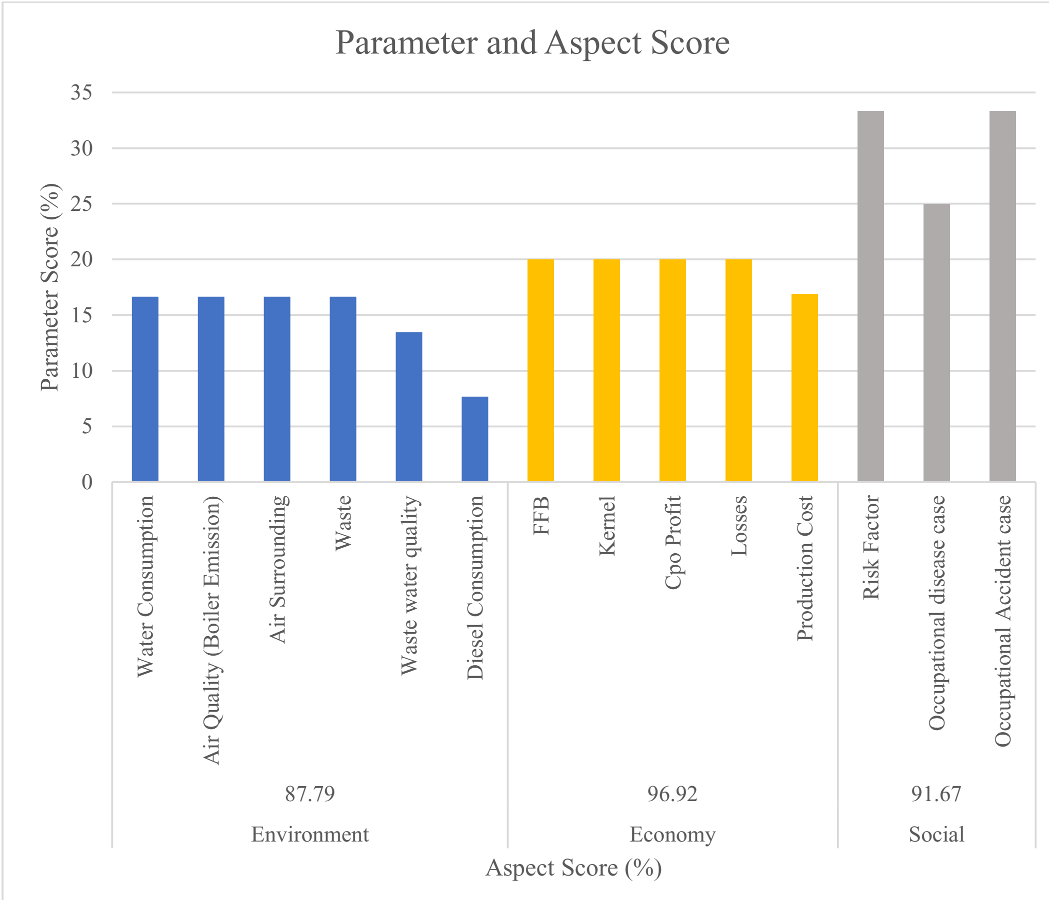

Fig. 8. The aspect score for mill A (Jamaludin et al., 2018).

Table 9
CO_2e emission reduction strategy and PI reduction percentage (Hashim et al., 2015).

Performance Indicator (PI)	Emission reduction strategy	PI reduction percentage
Fuel consumption (Natural Gas)	Natural gas-powered biopolishing and tractor	99%

Table 10
Carbon Footprint Accounting, Environment and Economic Index score before and after improvement.

Mill A				
Improvement strategy: replace diesel for transport with natural gas				
			Environment	Economy
	Mill Data	Before improvement	0.21 L/t	46.94 RM/t
		After improvement	0.002 L/t	50 RM/t
POMCF	$otCO_2e$	Before improvement	11.26 kg-CO_2e	n.a.
		After improvement	10.61 kg-CO_2e	n.a.
	tCO_2e of diesel consumption for transportation	Before improvement	0.66 kg-CO_2e	n.a.
		After improvement	0.0066 kg-CO_2e	n.a.
POMSI	PTT score (%) of diesel for transportation	Before improvement	0%	100%
		After improvement	100%	90%
	Index Score	Before improvement	92%	
		After improvement	95.55%	

n.a. – Not Applicable.

industries obtain a better judgement of the mitigation strategy to be applied. More mitigation options such as recycling water usage and biogas technology should be considered in future. An extended mitigation study that includes mathematical model to select optimal technology will be included in the future work.

Acknowledgement

This work was supported by Universiti Teknologi Malaysia under Research University Grant Q.J130000.2546.14H46, Q.J130000.2546.17H86, Q.J130000.2446.04G33 and Knowledge Transfer Programme grant R.J130000.7846.4L513 under Ministry of Higher Education Malaysia.

References

Ahamad, R., Yusop, Z., Salim, M.R., Haslenda, H., Zainon Noor, Z., 2015. 2014 Malaysia EPI methodology. Environ. Perform. Index Malays. 1, 37–49, 2014.
Ahmad, M.Z., Hashim, H., Yunus, N.,A., Muis, Z.A., 2015. Optimal solvent design for co2 capture process. Chem. Eng. Trans. 45, 1135–1140.
Amin, N.,A.,S., Talebian-Kiakalaieh, A., 2018. Reduction of CO2 emission by INCAM model in Malaysia biomass power plants during the year 2016. Waste Manag. 73, 256–264.
Ascui, F., Lovell, H., 2011. As frames collide: making sense of carbon accounting. Account. Audit. Account. J. 24, 978–999.
Bowen, F., Wittneben, B., 2011. Carbon accounting: negotiating accuracy, consistency and certainty across organisational fields. Account. Audit. Account. J. 24, 1022–1036.
Brander, M., 2016. Carbon accounting: ensuring a greener future. Social Responsibility and Sustainability. https://www.ed.ac.uk/about/sustainability/themes/climate-change/research/carbon-accounting.
Chand, P., Sirohi, S., Sirohi, S.K., 2015. Development and application of an integrated sustainability index for small-holder dairy farms in Rajasthan, India. Ecol. Indicat. 56, 23–30.
Department for Business, Energy & Industrial Energy (DEFRA), 2018. Methodology Paper for Emission Factors: Final Report. 2018 Government GHG Conversion Factors for Company Reporting.
Din, A.,K., 2017. Overview of the Malaysian Oil Palm Industry 2016. Economics & Industry Development Division.
Dong, G., Mao, X., Zhou, J., Zenga, A., 2013. Carbon footprint accounting and dynamics and the driving forces of agricultural production in Zhejiang Province, China. Ecol. Econ. 91, 38–47.
Feil, A., De Quevedo, A.D.M., Schreiber, D., 2015. Selection and identification of the indicators for quickly measuring sustainability in micro and small furniture industries. Sustain. Prod. Consum. 3, 34–44.
Fenner, A.,E., Kibert, C.J., Woo, J., Morque, S., Razkenari, M., Hakim, H., Lu, X., 2018. The carbon footprint of buildings: a review of methodologies and applications. Renew. Sustain. Energy Rev. 94, 1142–1152.
Gao, T., Liu, Q., Wang, J., 2014. A comparative study of carbon footprint and assessment standards. Int. J. Low Carbon Technol. 9 (3), 237–243, 1 September 2014. https://doi.org/10.1093/ijlct/ctt041.
Geibler, J.V., Cordaro, F., Kennedy, K., Lettenmeier, M., Rocher, B., 2016. Integrating resource efficiency in business strategies: a mixed-method approach for environmental life cycle assessment in the single-serve coffee value chain. J. Clean. Prod. 115, 62–74.
Grafakos, S., Enseñado, E.M., Flamos, A., 2016. Developing an integrated sustainability and resilience framework of indicators for the assessment of low-carbon energy technologies at the local level. Int. J. Sustain. Energy 36, 945–971.
Hashim, H., Abu Bakar, S.M., Lim, J.S., 2014. Green industry for low carbon economy: palm oil green assessment tool. Energy Procedia 61, 2759–2762.
Hashim, H., Ramlan, M.,R., Lim, J.,S., Ho, C.,S., Kamyab, H., Majid, M., Z, A., Lee, C.,T., 2015. An integrated carbon accounting and mitigation framework for greening the industry. Energy Procedia 75, 2993–2998.
Jamaludin, N.,F., Hashim, H., Muis, Z.,A., Zakaria, Z.,Y., Jusoh, M., Yunus, A., Murad, S., M, A., 2018. A sustainability performance assessment framework for palm oil mills. J. Clean. Prod. 174, 1679–1693.
Jasinski, D., Meredith, J., Kirwan, K., 2015. A comprehensive review of full cost accounting methods and their applicability to the automotive industry. J. Clean. Prod. 108, 1123–1139.
Kaewmai, R., H-Kittikun, A., Musikavong, C., 2012. Greenhouse gas emissions of palm oil mills in Thailand. Int. J. Greenh. Gas Contr. 11, 141–151.
Klaarenbeeksingel, F.,W., 2009. Literature review and proposals from the RSPO working group on greenhouse gases. Greenhouse gas emissions from palm oil production. https://www.rspo.org/files/project/GreenHouse.Gas.../Report-GHG-October2009.pdf.
Laurent, A., Olsen, S.,I., Hauschild, M.,Z., 2012. Limitations of carbon footprint as indicator of environmental sustainability. Environ. Sci. Technol. 46, 4100–4108.
Lim, C.I., Biswas, W.K., 2017. Development of triple bottom line indicators for sustainability assessment framework of Malaysian palm oil industry. Clean Technol. Environ. Policy 20 (3), 539–560.
Mazzoni, M., 2014. 3p weekend: 10 companies committed to sustainable palm oil. Triplepundit. Available online. https://www.triplepundit.com/2014/06/3p-weekend-companies-committed-sustainable-palm-oil/.
Malaysia Palm Oil Board (MPOB), 2018. Monthly Production of Oil Palm Products Summary for the Month of December 2017.
Musikavong, C., Gheewala, S.H., 2017. Assessing ecological footprints of products from the rubber industry and palm oil mills in Thailand. J. Clean. Prod. 142, 1148–1157.
Ministry of Natural Resources and the Environment (NRE), United Nations Development Program (UNDP) Malaysia, 2014. MYCarbon GHG Reporting Guidelines. National Corporate GHG Reporting Programme for Malaysia.
Rashidi, N.,A., Yusup, S., 2017. A review on recent technological advancement in the activated carbon production from oil palm wastes. Chem. Eng. J. 314, 277–290.
Rivera, J.L., Reyes-Carillo, T., 2016. A life cycle assessment framework for the evaluation of automobile paint shops. J. Clean. Prod. 115, 75–87.
Rosen, J., 2016. More companies are tracking carbon emissions — is it helping? https://www.greenbiz.com/article/more-companies-are-tracking-carbon-emissions-it-helping.
Roundtable Sustainable Palm Oil (RSPO), 2013. Principles and Criteria. Principles and Criteria for the Production of Sustainable Palm Oil.
Sahimi, N.,S., Turan, F.,M., Johan, K., 2017. Development of sustainability assessment framework in hydropower sector. Mater. Sci. Eng. 226, 012048.
Schmidt, M., 2009. Carbon accounting and carbon footprint – more than justdiced results? Int J. Clim. Change Strateg. Manag. 1, 19–30.
Stechemesser, K., Guenther, E., 2012. Carbon accounting: a systematic literature review. J. Clean. Prod. 36, 17–38, 2012.
Suttayakul, P., H-Kittikun, A., Suksaroj, C., Mungkalasiri, J., Wisansuwannakorn, R., Musikavong, C., 2016. Water footprints of products of oil palm plantations and palm oil mills in Thailand. Sci. Total Environ. 542, 521–529.
Tan, S., Jin Yang, J., Jinyue Yan, J., 2015. Development of the low carbon city indicator (LCCI) framework. Energy Procedia 75, 2516–2522.
Umar, M.,S., Urmee, T., Jennings, P., 2017. A policy framework and industry Roadmap model for sustainable oil palm biomass electricity generation in Malaysia. Renew. Energy (in press).
Wright, L.,A., Kemp, S., Williams, I., 2014. 'Carbon footprinting': towards a universally accepted definition. J. Carbon Manag. 2, 61–72.