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RESEARCH ARTICLE

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

Chye Ing Lim[1] | **Wahidul Biswas**[2]

[1] Faculty of Engineering and Science, Curtin University Malaysia, Miri, Sarawak, Malaysia

[2] Faculty of Science and Engineering, Curtin University, Perth, WA, Australia

Correspondence
C. I. Lim, Faculty of Engineering and Science, Curtin University Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia.
Email: chye.ing@curtin.edu.my

Abstract

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

KEYWORDS

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

1 | INTRODUCTION

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

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

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

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

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

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

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

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

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

2 | METHOD

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

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

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

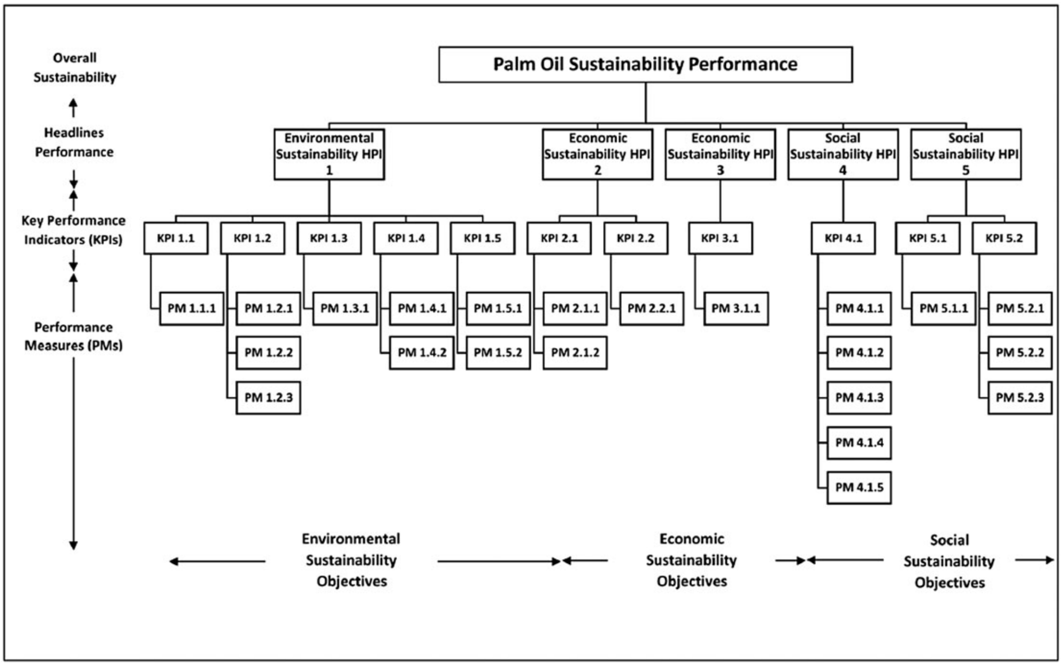

FIGURE 1 The Structure of Palm Oil Sustainability Assessment Framework (POSA) (Lim & Biswas, 2015)

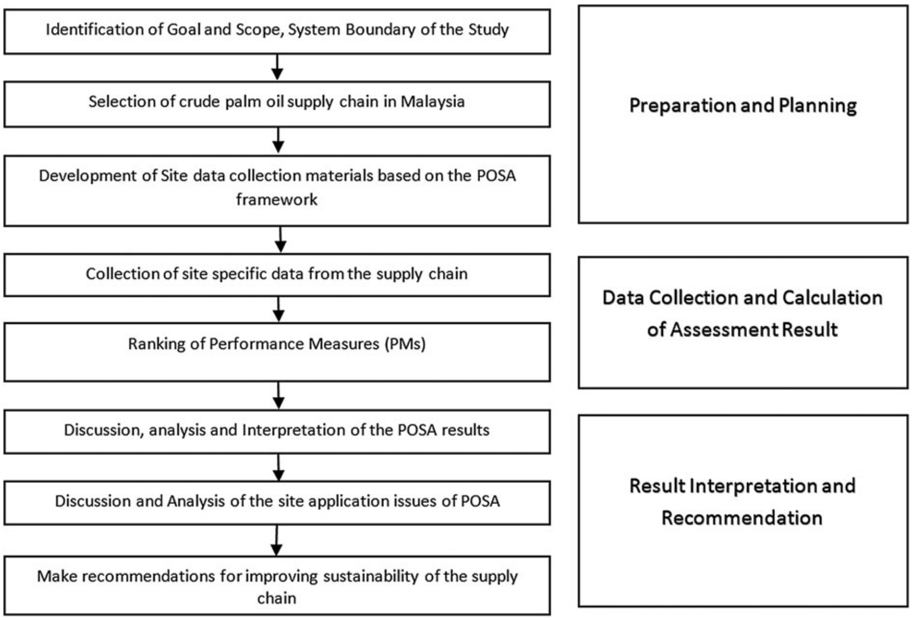

FIGURE 2 Procedure for applying sustainability assessment framework

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

2.1 | Goal and scope, system boundary of the study

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

2.2 | Selection of crude palm oil supply chain in Malaysia

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

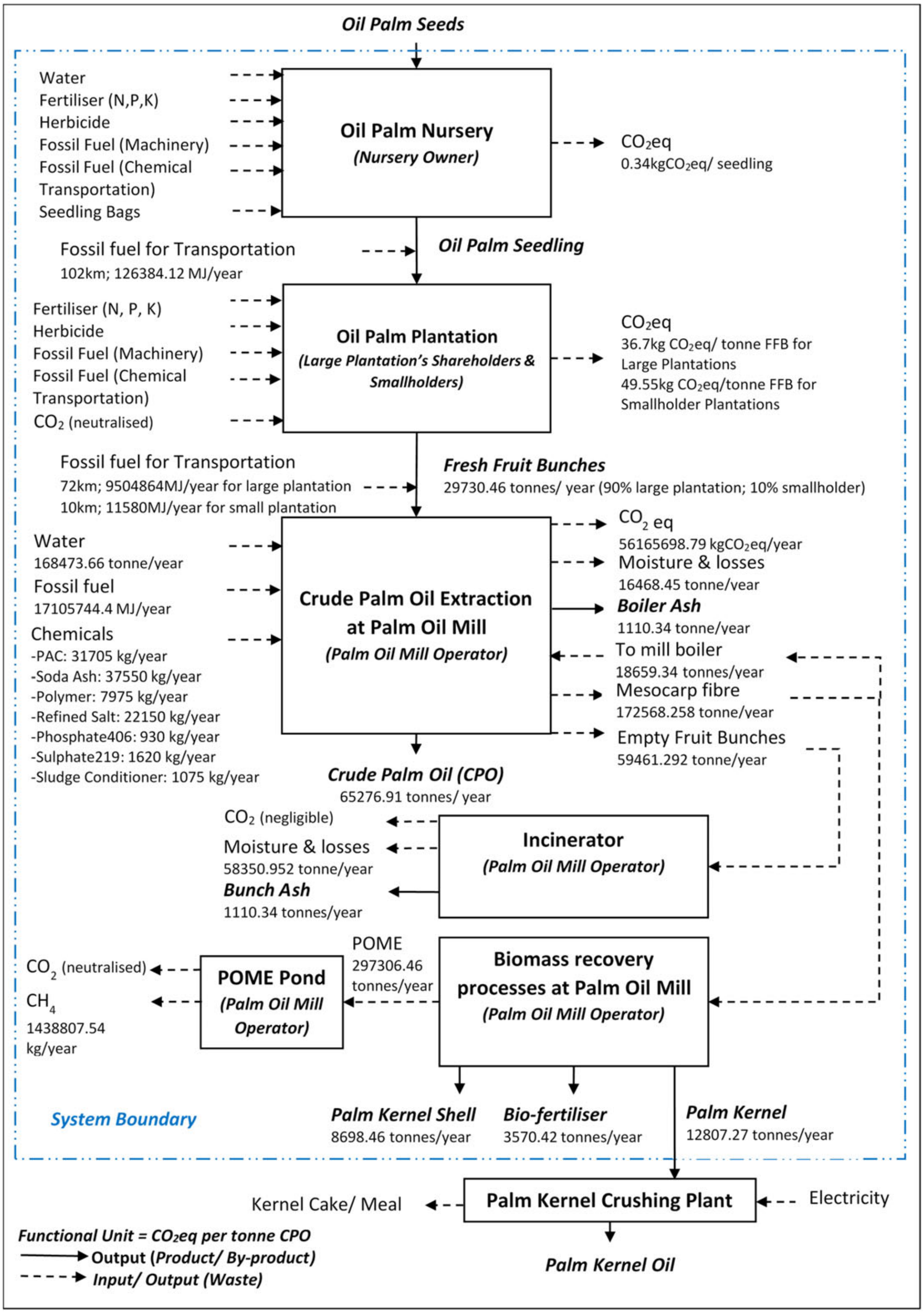

FIGURE 3 System boundary and inventory of Malaysia's most common supply chain for annual amount of crude palm oil production [Colour figure can be viewed at wileyonlinelibrary.com]

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

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

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

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

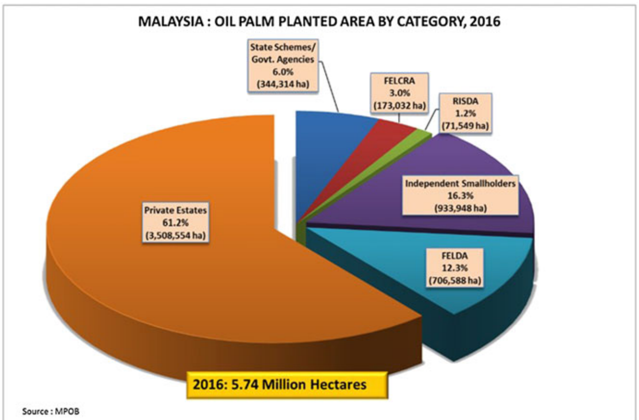

FIGURE 4 Oil palm planted area by category 2016 (MPOB, 2017) [Colour figure can be viewed at wileyonlinelibrary.com]

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

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

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

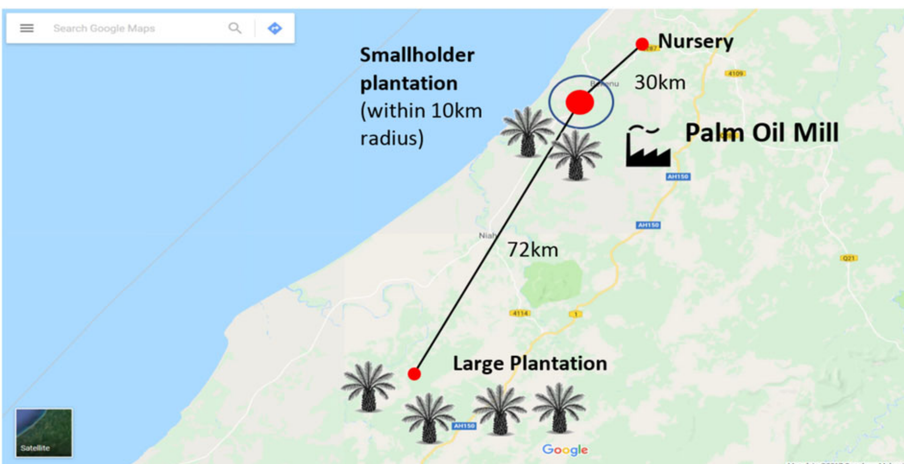

FIGURE 5 Location of the selected supply chain in Sarawak, Malaysia [Colour figure can be viewed at wileyonlinelibrary.com]

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

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

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

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

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

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

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

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

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

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

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

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

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

2.5 | Ranking of performance measures

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

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

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

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

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

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

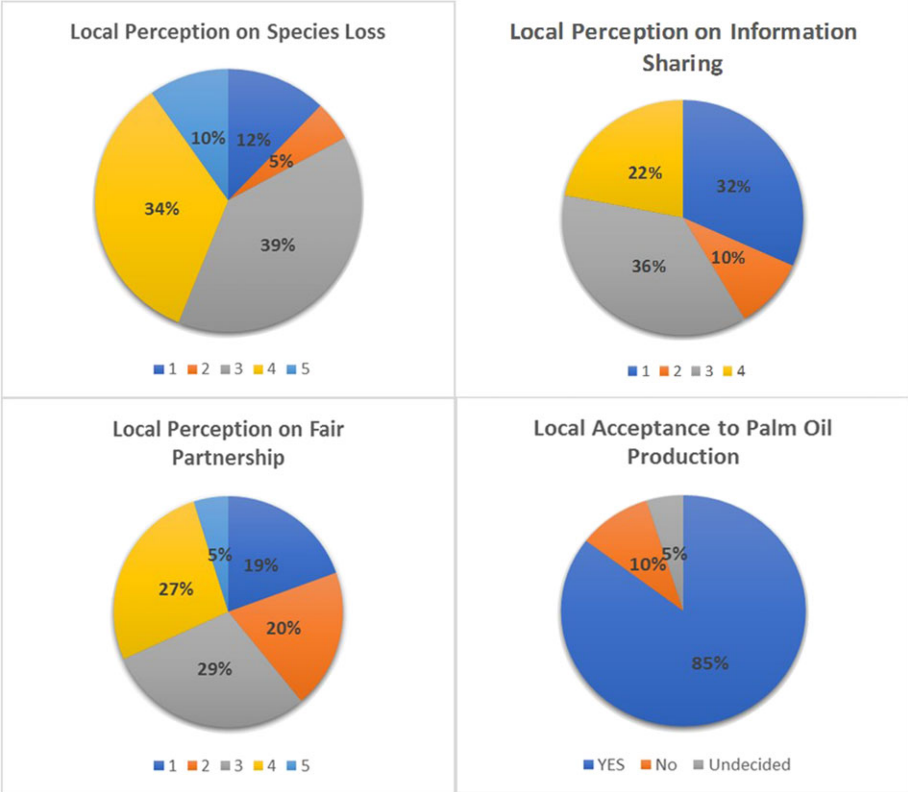

FIGURE 7 PMs based on expectation of the community [Colour figure can be viewed at wileyonlinelibrary.com]

3 | INTERPRETATION OF RESULTS AND RECOMMENDATIONS

3.1 | Triple bottom line implications of crude palm oil production

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

3.1.1 | Social bottom line assessment

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

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

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

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

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

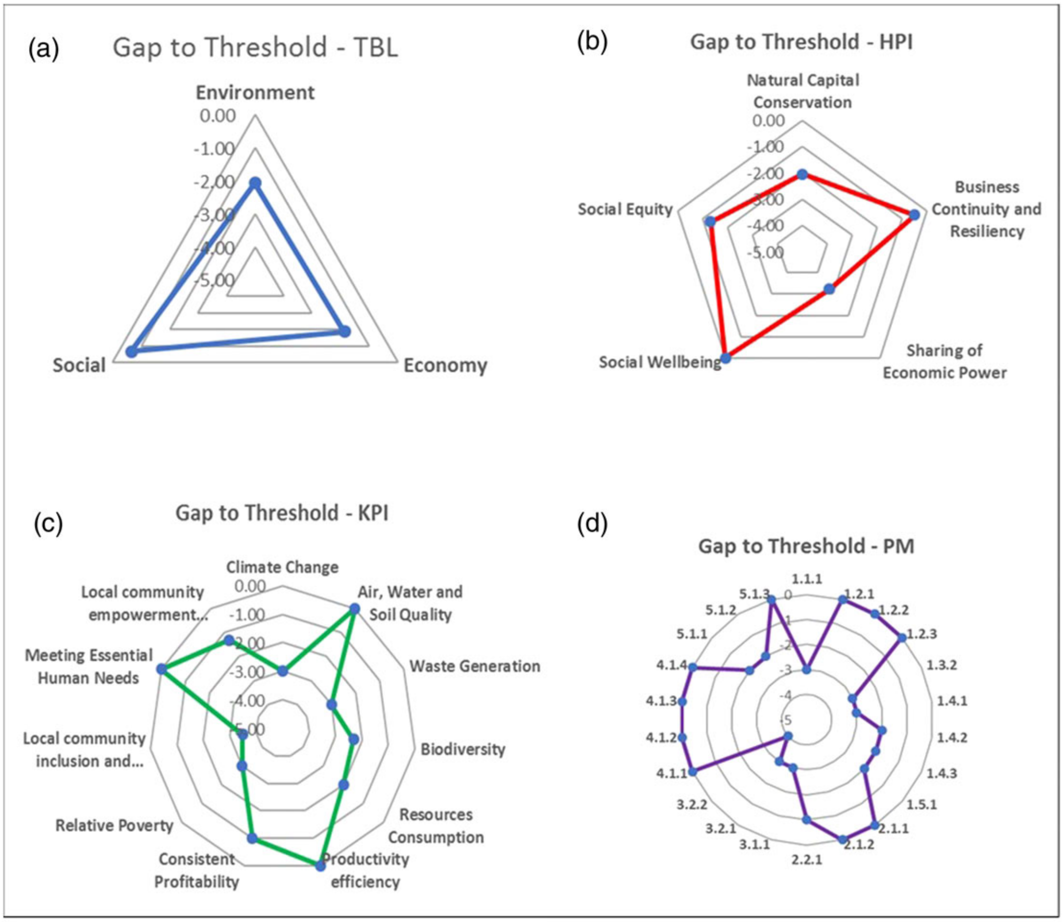

FIGURE 8 Sustainability outcomes using the POSA framework a) TBL Objectives b) HPIs c) KPIs and d) PMs [Colour figure can be viewed at wileyonlinelibrary.com]

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

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

3.1.2 | Environmental bottom line

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

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

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

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

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

3.1.3 | Economic bottom line

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

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

3.2 | Identifying causes of hotspots

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

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

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

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

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

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

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

TABLE 3 Sustainability improvement strategies

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

(Continues)

TABLE 3 (Continued)

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

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

3.3 | Sustainability improvement strategies

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

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

3.4 | Other recommendations

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

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

4 | CONCLUSION

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

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

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

ORCID

Chye Ing Lim http://orcid.org/0000-0001-9870-7757

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