Life Cycle Assessment of International Biomass Utilization

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Title:

Life cycle assessment of international biomass utilization: A case study of Malaysian palm kernel shells for biomass power generation in Japan

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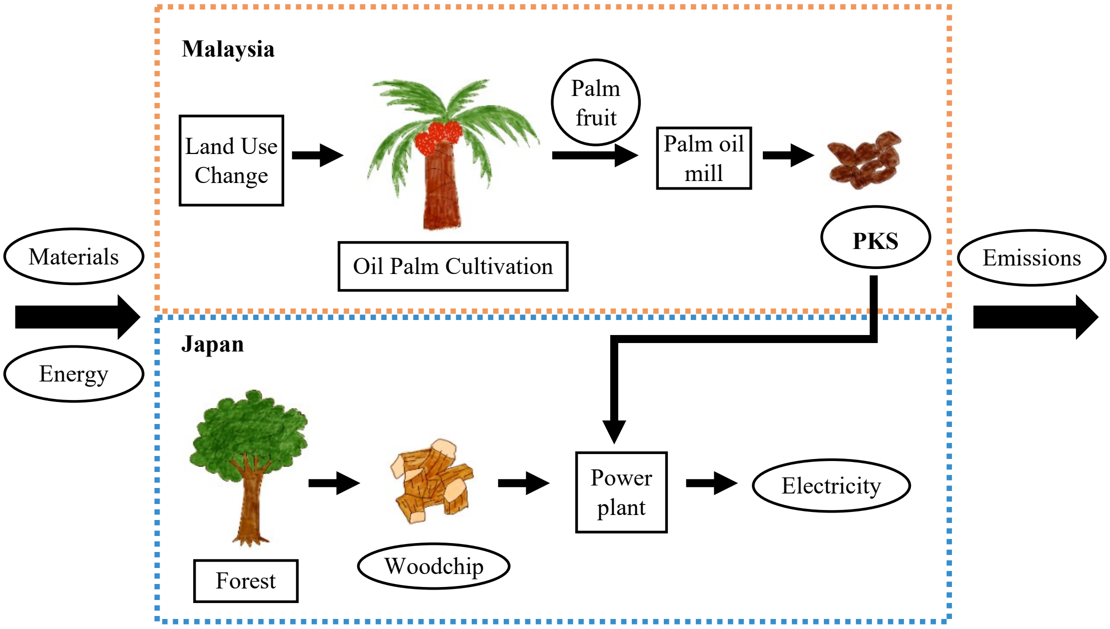
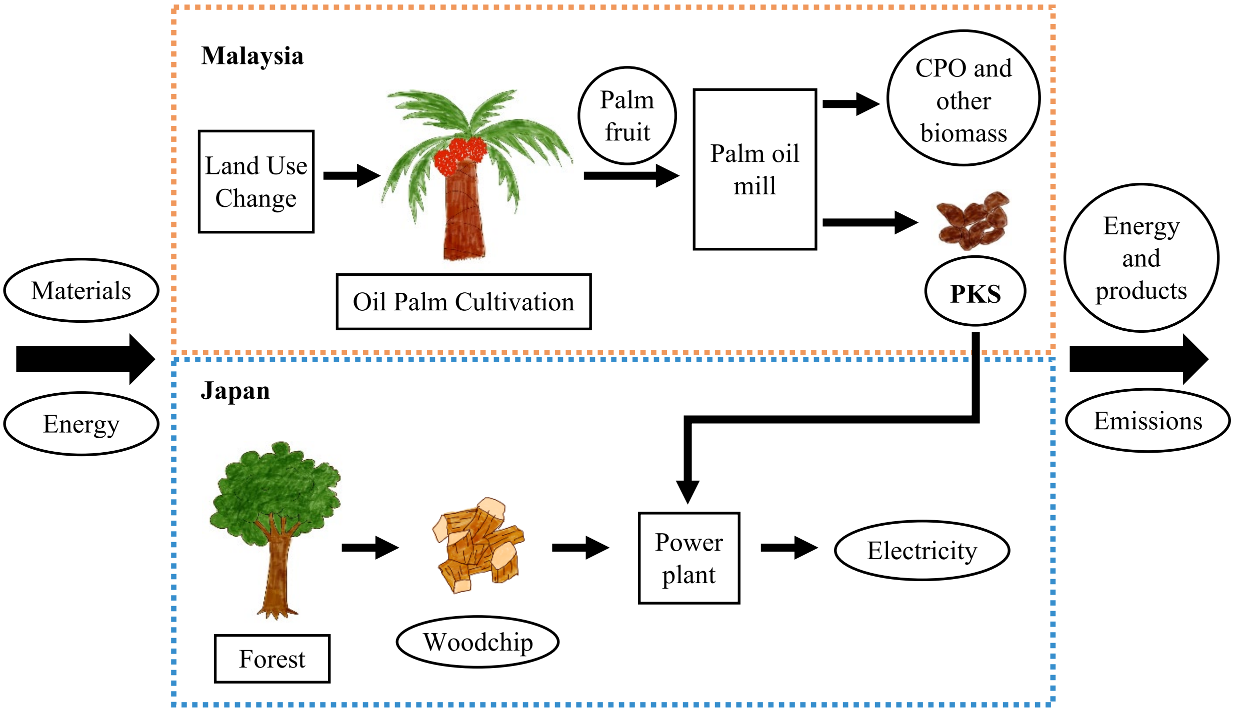
Abstract

Palm kernel shell (PKS) is a by-product in palm oil milling during the extraction of crude palm oil from fresh fruit bunches. PKS is a promising solid fuel to replace coal with its high calorific value. As Japan is moving towards renewable power to reduce carbon dioxide emissions, importing biomass as fuel sources is trending. In the past decade, PKS has been imported extensively into Japan for biomass-power generation, replacing fossil fuels under the feed-in tariff (FIT). PKS is easiest to utilize in existing power plants from an economic perspective reducing the cost for energy transition. However, the environmental impact of transporting such biomass across long distances have not been systematically assessed. Therefore, this work presents a life cycle assessment (LCA) of power generation with PKS in Japan. The LCA study covers land conversion of palm cultivation in Malaysia to biomass power generation in Japan. Factors considered include greenhouse gas (GHG) emissions, eutrophication and water footprint. Eight Malaysian scenarios were analyzed, based on different boiler fuel applications in the palm oil mill. In addition, eight Japanese scenarios were also considered, based on imported PKS-dominant and local woodchip-dominant power generation. This work noted the significant effect of land use change (LUC) on GHG emission. Based on results, imported PKS-dominant power generation in Japan is environmentally favorable than local woodchip-dominant power generation with careful selection of the biomass mix and power plant scale. PKS-based power generation contributes low GHG emissions which superior to fossil-based (coal, thermal oil, natural gas) power in Japan.

Graphical Abstract



PKS: Palm kernel shell



CPO: Crude palm oil, PKS: Palm kernel shell

Statement of novelty

This work reports the first life cycle impact assessment of palm kernel shell (PKS) in Malaysia from land use change to biomass power generation in Japan. By comparing four land use change types, four biomass fuel applications in the palm oil mill and two types of palm oil mill effluent treatment system in Malaysia and two shipping transport distances, two scales of power plant and two biomass mixes in Japan, this work identifies the best and worst case scenarios for PKS life cycle. With the life cycle thinking approach, the outcome of this work promotes sustainable utilization of biomass to minimize the imbalance in biomass resource share between countries.

Keywords

Greenhouse gas emission, land use change, water use and consumption, eutrophication, biomass resource sharing

Highlights

- Life cycle assessment of power generation with imported palm kernel shell
- The study covers land conversion of palm cultivation to biomass-power generation
- Factors considered include GHG emissions, eutrophication, and water footprint
- Different boiler fuel applications are considered in Malaysia
- Power generation via imported palm kernel shell and local woodchips were analyzed
- Best and worst environmental PKS life cycle scenarios were identified

Abbreviations table

Abbreviation	Definition
α	Leaching run-off fraction
AGB	Aboveground biomass
BGB	Belowground biomass
C_{act}	Actual pollutant concentration of intake water
C_{effl}	Pollutant concentration in effluent
C_{max}	Maximum acceptable pollutant concentration
C_{nat}	Natural concentration of pollutant
COD	Chemical oxygen demand
CPO	Crude palm oil
DOM	Dead organic matter
EFB	Empty fruit bunch
$Effl$	Effluent
ET	Evapotranspiration
FFB	Fresh fruit bunch
FIT	Feed-in tariff
GHG	Greenhouse gas
GWP	Global warming potential
HFO	Heavy fuel oil
JP	Japan
lgp	Period of growing
LPS	Low-pressure steam
LUC	Land use change
ML	Malaysia
PEFB	Pressed EFB
PKS	Palm kernel shell
POM	Palm oil mill
POME	Palm oil mill effluent
PPF	Pressed palm fiber
t	Metric ton
t-CO_2 eq	Ton of carbon dioxide equivalent emission
TP	Total phosphorus
WF	Water footprint
wt.%	Percentage by weight
Y	Crop yield
yr	Year
ΔC	Carbon stock change in ton carbon per year

1 Introduction

Due to global warming and depletion of natural resources, the transition from fossil fuel to more sustainable, less carbon-intensive energy sources has become more important. Hence, identifying and developing modern renewable energy sources is crucial. In 2015, the United Nations Sustainable Development Goals included Goal 7 to ensure access to affordable, reliable and sustainable energy for all [1]. To achieve this target, the International Energy Agency (IEA) developed a Sustainable Development Scenario (SDS) outlining a major transformation of the global energy system [2]. Thus, the share of renewables in global electricity generation has increased to 27% in 2019. However, according to the IEA, significant growth of renewable power is still needed. In order to meet the SDS target, at least half of the currently operating global power generation systems are required to be converted to power generation with renewable sources by 2030 [3].

The Japanese government targets to reach carbon-neutrality by 2050 [4]. Traditionally, Japanese energy systems are heavily dependent on imported fossil fuel, such as oil, coal and natural gas. As reported by the Ministry of Economy, Trade and Industry (2020) [5], prior to the Great East Japan Earthquake in March 2011, Japan's dependency on fossil fuels was reported as 81.2% (based on a primary energy supply basis), which increased to 87.4% in 2017 due to the shutdown of nuclear power plants. The increased consumption of imported fossil fuel for thermal generation has resulted in the increase of electricity prices and greenhouse gas (GHG) emissions in Japan recently. Between 2011 and 2016, the GHG emissions from the electric power sector increased by 54 million t-CO_2 eq (tons of carbon dioxide equivalent emission) due to the higher amount of power generation via thermal power plants as a substitute for nuclear power. Therefore, it caused an increase of about 4% of the total GHG emissions in Japan [6]. In order to decrease the GHG emission, a feed-in tariff (FIT) system was launched in 2012 to promote utilization of renewable energy for power generation [7]. As a result, biomass is identified as the most promising renewable energy source for the replacement of fossil fuels in the power generation sector. Most of the developed countries are adopting such initiative to reduce GHG emission and allow the consumers to pay for the premium price of electricity which utilizing renewable resources through FIT.

Palm oil is the largest vegetable oil in the world. As reported by the Malaysian Palm Oil Board (2019) [8], 19 million tons of crude palm oil (CPO) are produced in Malaysia annually. During the extraction of CPO from its fresh fruit bunches [9], various by-products are produced, such as palm kernel shell (PKS), empty fruit bunches, etc. According to Kasivisvanathan et al. (2012) [10], it is estimated that over 6 million tons of PKS are produced. Due to its high calorific value (<20 t-MJ·(kg)$^{-1}$) [11], PKS is identified as a promising choice in biomass power generation. In the current industry practice, part of the PKS is used as fuel sources for biomass boilers in the palm oil mills, while the remainder are exported to other countries. Recently, there is growing interest from the Japanese companies to replace fossil fuel with PKS due to its high availability and potential profitability. The PKS-derived power generation has already begun implementing in Japan through FIT supporting the economic feasibility. However, the environmental issues regarding the PKS is yet to be identified. As of 2018, a third of Japanese biomass power plants used PKS as a fuel source [12]. It was reported that approximately 0.3 million tons of PKS were exported in 2018 for power generation [13, 14]. Although PKS is a renewable energy source by nature, the transportation of such biomass to other countries may cause significant CO_2 emissions. Therefore, it is important to perform a life cycle assessment (LCA) for PKS as a bioenergy fuel source in Japan, which is the subject of the work.

On the other hand, identifying the application of PKS and local woodchip biomass in biomass power generation is important to create sustainable power generation in Japan. In recent years, harvesting of local wood is expected to increase in Japan, because aged trees have been accumulating in the country due to the past nationwide forestation program, coupled with the reduction of wood demand as fuel and material. Aged trees have several disadvantages, such as less carbon fixation, lower capacity of water resource conservation, and higher risk of landslides [15]. Therefore, there is an increasing interest in the harvesting of such aged trees as feedstock for woodchips and pellet production. As reported by the Japan Woody Bioenergy Association (2018) [16], Japan has 140–150 wood pellet manufacturing facilities that produced about 0.12 million tons of wood pellets in 2016.

In this work, a cradle-to-grave LCA was conducted for imported PKS from Malaysia for biomass power generation in Japan. In addition, utilization of local woodchip biomass for power generation was also considered. The objective of this work is to identify sustainable biomass sources from imported PKS and local woodchip biomass for power generation. The environmental impacts include GHG emission and water footprint (WF), and eutrophication effects are analyzed. This work examines the actual life cycle impacts induced by the international trading of biomass resources. At the same time, this work also analyzes potential future scenarios for the sharing of biomass among countries, which will also shift the effects of environmental impacts to an improved situation, while firmly interconnecting resource exporting and importing countries.

2 Life cycle and scenario settings

2.1 Settings in the PKS life cycle

This work covered the environmental impact analysis of the cradle-to-grave PKS life cycle from land use change (LUC) of oil palm cultivation in Malaysia to biomass-derived power generation in Japan, in accordance with the FIT system of Japan (Fig. 1). Sections 2.1.1–2.1.4 provide a detailed account of the PKS life cycle shown in Fig. 1. Different life cycle scenarios are analyzed in this work regarding the usage of PKS as boiler fuels in POM, and the application of local woodchip biomass and PKS on power generation. The scenarios are described in detail in section 2.2.

2.1.1 Land use change

About 68% of the world's tropical peatlands are found in Southeast Asia [17]. Miettinen et al. (2011) [18] reported that the proportion of the forest cover in the peatlands of Malaysia, Sumatra and Borneo regions declined from 77% in 1990 to 36% in 2010. The main reason for the disappearance of peatlands and other natural forests in this region is due to their conversion into agriculture cultivations and, in particular, to oil palm. Table 1 presents the oil palm cultivation area in Malaysia from 2013–2020. Note that about 12% extra land, or over 0.6 million hectares, was added to palm cultivation in Malaysia over a seven-year period [19].

It is noted that LUC affects the carbon stocks in the land. The changes in carbon stocks of aboveground biomass (AGB), belowground biomass (BGB), dead organic matter (DOM), soil and litter can be used to determine the effects of LUC. AGB includes the biomass in living vegetation (both woody and herbaceous) above the soil, which include stems, stumps, branches, bark, seeds and foliage [20]. BGB includes the biomass of all live roots [21] and DOM includes the stems and branches of deadwood 10 cm or larger in diameter [22]. The LUC effect can be calculated based on the Intergovernmental Panel on Climate Change (IPCC) guidelines on the GHG emissions from LUC, as shown in Eq. 1 [23]. In the latter, ΔC represents the carbon stock change in ton carbon per year. The change of land use into oil palm cultivations during the five-year period of 2014–2018 in Malaysia is taken into consideration in this work (Table 1). The detailed input data for the LUC analysis is presented in Table S1 of the supplementary material. Four main types of LUC into palm cultivations are considered, i.e., conversion from natural forests, peatlands, rubber cultivations and cleared lands. These land conversions are considered because there have been high levels of conversions into palm cultivation land in recent years [24].

$$\Delta C_{LUC} = \Delta C_{AGB} + \Delta C_{BGB} + \Delta C_{soil}\ \text{soil} + \Delta C_{DOM} + \Delta C_{litter} \qquad \textit{Eq. 1}$$

where,

ΔC_{LUC} = Carbon stock change by LUC
ΔC_{AGB} = Carbon stock change in aboveground biomass
ΔC_{BGB} = Carbon stock change in belowground biomass
ΔC_{soil} = Carbon stock change in soil
ΔC_{DOM} = Carbon stock change in dead organic matter
ΔC_{litter} = Carbon stock change in litter

2.1.2 Oil palm cultivation

Oil palm cultivation generates GHG emissions in various forms, including from the effects of land preparation for planting oil palm, from application of fertilizers and pesticides during cultivation and from the fossil fuel application in transporting the harvested FFBs to the POMs. The effects on GHG emissions during the conversion of land by the equipment and transportation vehicles, and the production of fertilizers and pesticides, are omitted in this evaluation. Based on statistics, the average effective harvesting period is given as 21 years because the continual productive lifespan of palm trees is around 25–30 years, including the first few years in the nursery and the maturing period [25–27]. Thus, the overall productive lifespan is taken as 25 years in this work. During the land preparation phase, the usage of excavators to construct the main, collection and subsidiary drains and the usage of trucks for FFB transportation to the mills are considered. Note that it is assumed that the average transportation distance between the plantations and the POM is 10 km. Diesel trucks with a load capacity between 7.5 and 12 t are selected as the transport mode for FFBs to the mills. The details of the land preparation, the transportation of FFBs and the applied chemicals are presented in Table S2.

2.1.3 POM operation

Detailed information of a typical Malaysian POM, taken from Foong et al. (2018, 2019) [28, 29], is used in this work. The process steps, as well as their input and output data, are given in Table S3 and Fig. S1 of the supplementary material. The environmental impacts can be linked with the material balance in Table S3 with a functional unit of one ton of PKS generation. As mentioned previously, the production of CPO increased rapidly to satisfy its high global demand over the past few years, as shown in Table S4 [19]. Table S3 shows that approximately 0.28 tons of PKS is generated in a POM for every ton of CPO produced. The environmental impacts of the POM can be determined based on the effects from each processing step, which start from the most to the least influential steps. The GHG emissions due to the application of biomass in a combined heat and power (CHP) system, as well as the treatment of solid and liquid wastes from the POM, were also taken into account.

Note also that a significant amount of palm oil mill effluent (POME) is generated in the POM, i.e., 2.5–3.5 t POME for every ton of CPO produced [30, 31]. POME contains high organic content with chemical oxygen demand (COD) (>50,000 $\mathrm{mg{\cdot}(L)^{-1}}$) and biological oxygen demand (>25,000 $\mathrm{mg{\cdot}(L)^{-1}}$), and total phosphorus content of around 510 $\mathrm{mg{\cdot}(L)^{-1}}$ [32]. Such effluent tends to be digested and produces biogas. Therefore, the environmental impact caused by POME is evaluated based on the emissions of biogas to the atmosphere [33]. Ponding treatment system is the most widely applied conventional POME treatment [34, 35]. It is estimated that an average of 28 m^3 biogas is generated in anaerobic ponds per m^3 of treated POME [33, 36]. The biogas normally consists of an average of 65% methane, 35% CO_2 and traces of H_2S in dry basis [37]. In order to reduce the environmental impact, various treatment systems with biogas capturing are being introduced [38–40].

As presented previously, PKS is commonly used as the biomass in a CHP system. Therefore, in this work, application of PKS in a CHP system in the POM is taken as the base case scenario. In other scenarios, the application of empty fruit bunches (EFB) and coal as alternatives to PKS in the CHP system were considered.

In the case of multiple outcomes (coproducts), allocation of total environmental burden to each outcome is commonly applied in LCA [41]. The same principle is applied for the case of the POM in this work, based on mass and economic allocations. The mass allocation of environmental burden is based on the production mass of each coproduct. Since this work focuses on the PKS life cycle, the environmental impact values are evaluated based on mass allocation of PKS production in the POM. On the other hand, economic allocation may also be performed based on the market values of the various coproducts of the POM, since most coproducts have good market values with high demands. The economic allocation performed in this work is based on the market values of the POM coproducts. The mass and economic allocation factors for each coproduct are given in Table S5. A comparison of mass and economic allocation is given in the discussion.

2.1.4 Transportation

Three main transportation systems are investigated in this work. These include the transportation of FFB harvest from plantations to the POM, transportation of PKS from the POM to Malaysian ports, and the international transportation of PKS from Malaysian ports to Japanese ports. It is noted that the biomass power plant is located on the shore or close to the port and the transportation distance between the port to the power plant is neglected.

Diesel trucks with a load capacity of 7.5–12 t are used for the transportation of FFBs and PKS in Malaysia. An average traveling distance from the plantation to the POM is assumed to be 10 km, and the traveling distance from the POM to the port is assumed to be 100 km. For the international transportation of PKS from Port Klang, Malaysia to Naha and Mombetsu Ports, Japan, container ships powered by heavy fuel oil (HFO) are selected. The distance between Port Klang, Malaysia to Japan is given as 5,228 km (Naha Port) and 8,458 km (Mombetsu Port). The fuel consumption and their effects on GHG emissions are analyzed and presented in the transportation section. The details of the transportation modes, applied fuels and transportation distances, and the parameters that influence the GHG emissions, are given in Table S2.

2.1.5 Woodchip biomass

As shown in Fig. 1, woodchip biomass is also considered as the feedstock for power generation. Therefore, the production of woodchip is analyzed. Because the woodchip is produced from aged trees, the

LUC of such biomass is not considered. The environmental impact from the harvesting of trees up to power generation is considered. Forest maintenance, harvesting, timber collection, the transport of the timber from the collection site to the chipping site and the chipping operation are considered in this section [42, 43]. The transport distance from the timber collection site to the chipping site was taken as 20 km. Note that it is assumed that the chipping site is collocated with the power plant and that the distance between the chipping site and the power plant is negligible. The information on woodchip consumption in Japan for energy use, the woodchip price and comparison with the imported PKS are given in Table S6 and Table S7 for understanding the current woodchip situation in Japan.

2.2 Scenario settings

Based on the current industry practice, most POMs utilize pressed palm fiber (PPF) and PKS as the biomass fuel in CHP systems [44, 45] for power and steam generation. On the other hand, most of the EFBs are returned to the plantation as a mulching material [46]. In order to enhance the sustainability of the industry, all the palm-based biomass (e.g., EFB, PKS, PPF, etc.) can be converted into various products [47, 48]. Therefore, the application of PPF, PKS, EFBs and coal in various combinations as boiler fuels in the POM is analyzed. In addition, to compare the environmental impact of biomass with fossil fuel in the CHP system, utilization of coal is considered as an alternative option.

Table 2 shows the alternative scenarios which are considered in Malaysia. Note that four types of boiler fuel are considered: (i) base case - "PPF + PKS", (ii) Option 1 - "PPF + EFB", (iii) Option 3 - "PPF + coal" and (iv) Option 4 - "coal". Two types of palm oil mill effluent (POME) treatment are included in this study: (i) POME treatment without any biogas capture (termed as "Open pond") and (ii) POME treatment with biogas capture and flare system ("Biogas capture").

The Japanese scenarios are formulated based on the biomass mix used in the power plant. As shown in Table 3, two combinations of biomass mix are considered: (i) "Local-dominant" with a majority of local woodchips (30% PKS + 70% woodchips) and (ii) "Import-dominant" with PKS as the majority solid fuel (90% PKS + 10% woodchips). The shipping transport distance from Klang port (Malaysia) to Naha port (Japan) was used as the "shortest" distance and that from Klang port (Malaysia) to Mombetsu port (Japan) as the "longest". Two sizes of power plants (a "low" one of 1,990 kW and a "high" one of 200,000 kW) are considered.

Malaysian scenarios are displayed as "M" and Japanese scenarios are as "J". The base scenario (Scenario M1+J1) represents the conventional CPO production with the application of PPF and PKS as fuels in a CHP system with open pond treatment in Malaysia, and exporting PKS over the shortest distance as solid fuel for a 1,990 kW power generation in Japan with a biomass mix of 30% PKS and 70% woodchips.

2.3 Assessment setting: Indicators

In this work, the life cycle impact assessment of PKS is evaluated with consideration of GHG emissions (CO_2, methane (CH_4) and nitrous oxide (N_2O)) within the life cycle. The 100-year time horizon global warming potential (GWP) values related to CO_2 (CH_4: 28 and N_2O: 265) are taken from the IPCC Fifth Assessment Report—2014 [49].

The consumption of water is also another important element in evaluating the sustainability of a life cycle. Therefore, the WF is used as the measure of fresh water consumption directly and indirectly in the supply chain. In this work, three WF categories including blue, green and gray [50] for palm cultivation and the operation of POMs, are taken into consideration. Blue WF represents the use and consumption of surface and groundwater along the supply chain. Green WF represents the use and consumption of water from precipitation. Gray WF refers to the use of fresh water to improve the quality of wastewater to meet the discharge standards. More detailed calculations of WF can be found in the WF assessment manual of Hoekstra et al. (2011) [50].

Eutrophication effects by cultivation of oil palm and POM operations are also evaluated in this work. The degree of phosphorus release within the considered system boundary is analyzed. The eutrophication effect during the cultivation stage with the application of phosphorus fertilizer is computed. The POME discharge, which has a high phosphorus content, is also determined as the eutrophication effect of the POM. The eutrophication evaluation is performed based on the unit mass of phosphate release to the environment. Environmental impacts data were gathered from commercially available ecoinvent [51] and inventory database for environmental analysis (IDEA) [52] databases and, published articles as well.

3 Results

3.1 Effect on GHG emissions in PKS life cycle elements

3.1.1 Land use change

Converting natural land into croplands is unavoidable with the ever-growing population and the demand for food. Previous land use purposes in Malaysia, prior to oil palm cultivation, are presented in Gunarso et al. (2013) [24] for the period 2006–2010. As presented, most of the unused (cleared) lands (35%), including landscapes impacted by fire, portions of estates undergoing replanting procedures and deforested areas, became palm plantations. 30% of the converted land is from less profitable croplands. Around 45% of cropland conversion is from rubber cultivations, representing 13.5% of total land conversion. Other conversions are from natural forests (28%), peatlands (6%) and grasslands (1%).

Table 4 presents the effects of LUC, considering the complete conversion from each LUC category and their respective conversions. Even though the actual percentage of LUC from peatland was very low (6%) in recent years, it contributes a significant amount of GHG emissions (36.2%). This is due to the peatland being recognized as high carbon stock areas [53]. The water-saturated soils in peatlands constrain the wood and roots from complete decomposition, making the peatland a huge carbon storage pool. Therefore, conversion of peatlands to croplands releases a substantial amount of CO_2 during logging and drainage periods [54–56]. Note also that the highest contribution to GHG emissions of 54.2% results from the conversion of natural forest.

3.1.2 Oil palm cultivation

GHG emissions during oil palm cultivation is presented in Fig. 2. It shows that fertilizer application has the highest GHG emission, followed by FFB transportation and land preparation. Since the GHG emission outcomes are averaged on a yearly basis, the contribution from land preparation is relatively low (8%) compared with the contributions by the application of fertilizer and the diesel consumption in FFB transportation.

Note also that GHG emissions generated from the transportation of FFB will vary depending on the distance from the oil palm plantation to the POM and the transportation mode. As oil palm requires high nutrient content for the production of FFB, ammonium sulfate is extensively used as a nitrogen-rich fertilizer in palm cultivation in the Southeast Asian region [57]. Therefore, to determine the GHG emissions resulting from the fertilizer application, the effects of nitrogen in the ammonium sulfate fertilizer are considered (Table S2).

3.1.3 Palm oil mill operations

A typical CPO extraction process in a POM is given in Fig. S1. This work considered the application of different biomass fuels in the boiler as different scenarios. In POM operation, process units associated with POME generation and consumption of fossil fuels contribute extensively to GHG emissions. POME is a major environmental concern in a POM, contributing the majority of the GHG emissions from a POM.

The effects of each boiler fuel application considered in this work are given in Fig. 3. The coal-fired operation is determined as the least favorable option. Conversely, the palm-based biomass application in a CHP system decreased the level of GHG emissions. The main boiler fuel, PPF has a high calorific value (19.06 $MJ\cdot(kg)^{-1}$), less moisture content (37 wt.%) and high availability (8.18 million t in 2017) [58] making it suitable as a boiler fuel. Co-firing of PPF and EFB displayed similar GHG emission levels to co-firing of PPF and PKS. On comparing the calorific values (EFB: 18.88 and PKS: 20.09 $MJ\cdot(kg)^{-1}$), moisture contents (EFB: 67 and PKS: 12 wt.%) and the availability of EFB with PKS (EFB: 7.78 and PKS: 4.72 million t in 2017) [58], it was found that replacing PKS with EFB in the boiler will be beneficial in terms of securing the availability of PKS to export for biomass power generation.

With the high levels of methane in biogas and its high GWP (28 times higher than CO_2), the direct release of biogas into the atmosphere is undesirable. Fig. 4 compares the extent of GHG emissions considering POME treatment. Lately, there is a tendency to capture biogas in POMs due to local authority requirements. However, some POMs still do not capture biogas due to costs and practical difficulties. For POMs equipped with a biogas facility, the collected biogas can be beneficial as a renewable energy source to produce electricity for the POM and to feed surplus electricity to the industry directly or through the national grid, if within a feasible distance. The utilized captured biogas can then be flared to reduce the environmental impact by releasing CO_2 instead of methane.

3.1.4 Transportation

In this section, local transportation of harvested FFBs from the plantation to the POM and PKS from the POM to the shipping port, and international transportation of PKS from the Malaysian port to the Japanese port are considered. Fig. 5(a) presents the GHG emissions when PKS is only exported. The transport interactions where PKS is exported as a raw material and not used as boiler fuel are presented in scenarios M2, M3, M4, M6, M7 and M8. Fig. 5(b) presents the GHG emissions when PKS is used for boiler fuel and for exporting. These are the transportation interactions in scenarios M1 and M5 where PKS is burned as boiler fuel in the POM and the remainder is exported.

International transportation of PKS between Malaysia and Japan displays a higher contribution to emissions than local transportation of FFB and PKS. FFB transportation shows a higher contribution than the PKS transportation, even though the FFB transportation distance considered was 10 times lower compared with the PKS transportation distance. Considering the actual cultivation and POM details applied in this work, the FFB production is higher than PKS. Thus, a higher amount of FFB is being transported from the oil palm plantation to the POM, compared with the amount of PKS transported from the POM to the port.

3.2 Contribution of scenarios to total GHG emissions

3.2.1 Malaysian scenarios

GHG emissions in the PKS and woodchip life cycles for various scenarios (without LUC effect) are shown in Fig. 6. In the Malaysian scenarios, the POM is the major contributor of the overall GHG emissions (Fig. 6(a)). It is noted that a significant reduction in GHG emissions can be achieved from biogas capture via a closed pond (scenarios M5 to M8), which is in line with Fig. 4.

As shown in Fig. 6, scenario M4 has the highest GHG emissions of all the scenarios where the POM is operated with a coal-fired boiler with no biogas capture in the POME treatment (open pond). On the other hand, the most environmentally favorable scenario is M5, in which the POM is operated with co-firing of PPF and PKS in the boiler and with biogas capture in the POME treatment (closed pond). The GHG emissions from scenarios M5 and M6 are relatively similar.

The local transportation in Malaysia and oil palm cultivation do not contribute significantly to GHG emissions. The uncertainties in the transportation distances and transportation modes are not taken into account in this work. The low GHG emissions' effect from cultivation is justifiable due to lower fertilizer usage in oil palm cultivation compared with other crops. Note that for these scenarios, the effect of deforestation was not included in oil palm cultivation in this work.

3.2.2 Japanese scenarios

The GHG emissions from transporting PKS between Malaysia and Japan, and the application of local woodchip in biomass power generation in Japan, are considered in different Japanese scenarios (Fig. 6(b)). International transportation of heavy loads of PKS in import-dominant scenarios (90% PKS in scenarios J5 to J8) contributed considerably more to GHG emissions than in the local-dominant scenarios (70% woodchip in scenario J1 to J4). The scale of the biomass power plant affects the extent of the GHG emissions. Therefore, in this work, a high efficiency for the "high" plant scale (200,000 kW) with low GHG emissions are considered in scenarios J3, J4, J7 and J8. A "low" power plant scale (1,990 kW) is considered in scenarios J1, J2, J5 and J6. A coal power plant has rather higher capacity compared to a biomass power plant [59]. In biomass power generation, the powerplant scale is not very huge due to the risk of procurement as a fuel. Thus, the efficiency of the coal-based power generation is higher compared to the biomass-based power generation. In comparison with current power plant efficiencies (Joule-electricity per Joule-fuel) in Japan, coal-based power plants display around 37-45% of power generation efficiency [60], while the biomass-based power plants achieve only 15-30% of power generation efficiency. However, the efficiency of biomass-based power generation tend to be increased with the future enhancements in the biomass-based power generation in Japan.

3.2.3 Combined scenarios for overall PKS life cycle

To analyze the overall PKS life cycle, a combination of the Malaysian and Japanese scenarios are presented in Fig. 6(c). It is noted that the significant effects of the POM in the Malaysian scenarios and the woodchip procurement in Japan in the PKS life cycle, can easily be identified in Fig. 6(c). Thus, the importance of improving the elements in the CPO production process in the POM, and the proper selection of the biomass mix, and the scale of the biomass power plant are noted.

In Fig. 6(d), the GHG emissions of all 64 possible scenario combinations of the PKS life cycle (excluding the LUC effects) are shown. The highest GHG emission of 0.82 kg-$CO_2 \cdot (kWh)^{-1}$ is obtained in the combined scenario of M4-J2. The lowest GHG emission of 0.09 kg-$CO_2 \cdot (kWh)^{-1}$ can be obtained from the M5-J7 scenario, which is 9 times lower than for the M4-J2 scenario. This is compatible with the individual scenarios presented in Fig. 6(a) and Fig. 6(b). A conventional coal-based power plant in Japan contributes for 1.01 kg-$CO_2 \cdot (kWh)^{-1}$ of GHG emission (calculated based on Ecoinvent databases). Still, the application of the highest GHG emitting scenario in this study: M4-J2, contributes for 19% less GHG emission compared to the conventional coal-based electricity production.

3.3 Water footprint assessment in cultivation and POM operations

The contributions of blue, green and gray WFs in oil palm cultivation and POM operations with consideration of POME treatment, are presented in Fig. 7. In this analysis, "POME treatment" indicates the dilution of POME to reach the allowable discharge water quality standards. In the cultivation, the green WF shows around 93.7% of the total WF, which resulted from precipitation and the occurrence of evapotranspiration in oil palm trees during the 25 years of cultivation. The blue WF represents the usage of water with fertilizer and pesticide applications, which is a small contribution (2.6%) compared with the green WF. The gray WF in cultivation contributes 3.7%, which represents the amount of water needed for diluting chemical concentrations in fertilizers and pesticides to reach the required environmental standards. Thus, during cultivation, the water usage with chemical application (blue WF) is lower than the water requirement for diluting chemicals (gray WF). It is assumed that the water requirement during cultivation can be fulfilled by the high levels of precipitation in major palm oil countries (Malaysia and Indonesia), and that no irrigation water is needed.

The WF in POMs with POME treatment reported about 99% of gray WF, since the main usage of water is required in the POME treatment. As mentioned previously, POME is heavily polluted in nature and contains around 50 g/L of COD [32]. Therefore, treating POME is extremely important considering the potential environmental impacts. The consideration of POME dilution to reach the allowable discharge standard in Malaysia (COD: 0.2 g/L) [61] demonstrates the necessity of water supply in considerable amounts at POMs.

In a POM, water is required mainly in the clarifier and the boiler operations. For a typical POM without POME treatment, only the blue WF is applicable. As shown in Fig. 7, the WFs are around 628 m^3 for cultivation, 160 m^3 for POMs with POME treatment and 0.6 m^3 for the POM operation. Oil palm cultivation demonstrates a higher water consumption compared with the POM operations. The consumption of water for diluting POME is significant.

3.4 Eutrophication effects from palm cultivation and POM operations

With the fertilizer application in oil palm cultivation and the high presence of nitrogen and phosphorus in POME, the occurrence of eutrophication is highly probable. In this analysis, eutrophication effects based on phosphorus emissions were considered. The main phosphorus contribution is from the application of rock phosphate fertilizer, which is performed at the beginning of oil palm cultivation [62].

The gradual release of phosphorus during the cultivation period is considered in evaluating the eutrophication effects on cultivation. Fig. 8 illustrates the outcomes of the eutrophication effects without allocation. In comparison with the contributions from the POMs without POME treatment, the effects from cultivation are about three times lower. The significantly higher eutrophication effect from the POM operation occurs when POME treatment is not performed.

By applying the ponding system for treating POME to reach the allowable phosphorus discharge standard of 5 $mg \cdot (L)^{-1}$ [61], the eutrophication effects are reduced to much lower levels than that from the oil palm cultivation.

3.5 Total environmental impacts assessment

Integration of GHG emissions with eutrophication effects and comparison with the WF evaluation can be performed to identify the effect of total environmental impacts on the PKS life cycle. The damage to the ecosystem, considering the number of species lost in a year, is evaluated by integrating GHG emission values with eutrophication values in each scenario combination (Fig. 9), using the methodology in ReCiPe 2016 [63]. The highest contributions by the scenario combinations associated with the M4 scenario, and the lowest contributions by the scenario combinations associated with the M5 scenario, are clearly shown in Fig. 9.

To identify the best and the worst scenario combinations, the ecosystem quality of the M4 and M5 scenarios are further evaluated with WF values (Fig. 10). The WF outcomes indicate the low water consumptions in the J1–J4 scenarios, compared with the high water consumptions in the J5–J8 scenarios. This is completely dependent on the amount of PKS usage in the biomass mix in the power plant. Considering the outcomes of the ecosystem damage and the WF values in Fig. 10 (a and b), the best and the worst scenario combinations can be identified as M5+J3 and M4+J6, respectively. This does not agree with the exact outcomes of GHG emissions displayed in Fig. 6 (d). However, the heavy influence of the Malaysian scenarios on the PKS life cycle are clearly demonstrated in terms of GHG emissions and total ecosystem damage outcomes.

4 Discussion

4.1 Alternatives in Malaysian PKS supply chain considering uncertainties

4.1.1 LUC and palm cultivation

Southeast Asia covers 15% of the world's tropical forests while facing heavy deforestation [64, 65], partially due to the expansion of the oil palm sector, for years. However, it is a misconception to claim that all palm cultivations originated from forest conversion. Malaysia has maintained a forest cover of nearly 60% for several years and in 2020 it was around 58% [66]. LUC resulted in significant contributions to GHG emissions, especially from peatland and natural forest conversions (Table 4). To illustrate the high contributions to GHG emissions by LUC, Fig. 11 compares the effects of LUC on the PKS life cycle, considering the best (M5+J7) and worst (M4+J2) scenarios. Peatland conversion contributed over 99% of GHG emissions in the best scenario and 96% in the worst scenario, while the cleared land conversion reduced the GHG emissions in the PKS life cycle. Similar results are also reported in other studies [67].

Because the cleared land conversion resulted in a negative contribution to GHG emissions, re-cultivation of previous oil palm and rubber plantations, as well as cultivating in degraded lands, should be promoted to reduce the impact of LUC. The application of marginal lands in producing biomass for bioenergy applications is another possibility to minimize GHG emissions in LUC [68]. In every case, the actual carbon stocks must be monitored and examined. GHG emissions by the cropland conversion depends largely on the individual cropland. Rubber plantations displayed a contribution of about 10% to GHG emissions from its LUC (see Table 4). Although converting from low economic value crops appears to be economically encouraging, the environmental impact of such conversion is uncertain. Therefore, a systematic analysis and optimization model is needed to plan for sustainable cropland expansion and conversion [69].

In oil palm cultivation, application of chemical fertilizers contributes significantly to GHG emissions. The extent of GHG emissions in cultivation is site specific, depending on the different types of chemical fertilizer applied. Since no chemical is added in the CPO production process, the generated POME does not contain foreign substances other than the oil palm composition itself. To minimize the effects of chemical fertilizer application, replacing chemical fertilizers with bio-fertilizer produced from palm-based biomass (EFB, decanter cake and POME sludge) is recommended. Furthermore, introduction of new oil palm variants and improved harvesting techniques (to reduce harvesting time and improve collection methods) can also improve the overall efficiency and reduce waste in the plantations.

4.1.2. POM operations

As presented previously, various types of palm-based biomass are generated during the extraction of CPO. Such biomass can be converted into energy sources [70, 71] or various value added products [47, 72]. Since a number of the palm biomass products (PPF, PKS and EFB) have good calorific value, they are commonly used as fuel sources in biomass boilers. In current practice, PPF is fully utilized in boilers, while PKS is applied to supplement any shortage of PPF. EFB is also mixed with other biomasses as fuel sources. However, due to their high moisture content, modification is required for conventional boilers. With high export demand for PKS, EFB has been identified as a potential source for PKS replacement in biomass boilers. The effective application of biomass resources is important to achieve sustainable production of CPO.

Based on the presented results (Fig. 4), the application of closed anaerobic digestion pond systems along with biogas collection systems is recommended. At the same time, POME can be used to produce value-added products such as biofertilizers [73, 74] to achieve further GHG emission reductions. It must also be noted that optimizing the ratio of biomass as fuel source for biomass boilers is crucial. A carbon-negative and energy-positive process should provide the required energy from part of the biomass, while the remainder of the biomass can be used for biochemical and bioenergy production.

4.2 Comprehensive interpretation of the palm-based biomass assessment with current analysis limitations

In the previous section, the detailed environmental impacts of each scenario in a PKS life cycle are presented. Based on the mass and price of the palm by-products in Table S5, the environmental burdens of the PKS life cycle for the baseline scenario (M1+J1), the best-case scenario (M5+J7) and the worst-case scenario (M4+J2) are shown in Fig. 12. It should be noted that the GHG values in the economic allocation are less than that of the mass allocation values.

In general, the environmental burden of the PKS supply chain affects both countries. GHG emission is considered as a global issue, whereas water consumption and eutrophication are regarded as local environmental issues. Considering the temporal and spatial difference of environmental impacts [75], the prioritization of technology implementation should be discussed for both the Malaysian and the Japanese life cycles.

In the case where eutrophication has the higher priority, POME treatment must be implemented at the expense of gray water consumption. With sufficient precipitation, the green WF for cultivation can be ignored and the gray water demand can be met from green water sources, reducing the WF with POME treatment. In cases where limited water supply is encountered at the agricultural site, and where irrigation is necessary, the gray water for POME treatment may be supplemented from blue water sources.

A new production scheme should be economically viable, socially beneficial and have low environmental impact in achieving its sustainable production and consumption. Because it is quite impossible to evaluate all three sustainable pillars in a single study, the environmental impacts were prioritized in this work.

The robustness of the trading of PKS should also be carefully assessed. As occurred in the transboundary recycling of polyethylene terephthalate recycling, a political decision could suddenly stop the supply chain, even though the life cycle can reduce GHG emissions [76]. If the FIT prices for biomass power generation declines in the near future, the PKS supply chain may not be sustained by the Japanese market. Additionally, since PKS is available locally in Malaysia, the consumption of fossil fuels in Malaysia should be reduced by utilizing PKS. Such possible changes should be examined collectively from socioeconomic and sociotechnical viewpoints. The outcomes will impact all stakeholders in the PKS supply chain, in a similar way as what happened for biomass resources in Japan [77]. Continuous examination and improvement should be conducted within Malaysia and Japan with quantitative assessments similar to what is presented in this work.

4.3 Import- and local-dominant biomass power generation

According to the results presented in Fig. 6 and Fig. 9, the best environmentally favorable scenario combination (M5-J7) obtained in this work is an import-dominant scenario case. Imported biomass resources such as PKS can be easily transported to the shore where large thermal power plants are located. Through the division of roles between local and imported biomass, more renewable energy sources could be implemented in the energy generation mix in Japan.

Currently, the infrastructure system in Japan for local biomass usage is limited and PKS is a potential accelerating material for enhancing the biomass infrastructure system in Japan. Local biomass can be utilized at regional energy centers for industrial symbiosis [78], the scale of which can be designed with consideration of forest resource management [79]. By combining imported and locally available biomass resources, industrial residues (e.g., by-products of livestock industries, food processing and sawmills) can be utilized effectively. Considering life cycle GHG emissions of Japanese power generation, i.e., 0.011 to 0.103 kg-CO_2eq·$(kWh)^{-1}$ for renewable power sources and 0.430 to 1.080 kg-CO_2eq·$(kWh)^{-1}$ for fossil-based power sources [80], outcomes of environmental assessments from this work could demonstrate potential benefits from import-dominant scenarios. In terms of the economic feasibility of the import or local dominant power generation, the future potential on import and local resources price increase and the availability need to be identified with referring to the Tables S6 and S7.

5 Conclusions

In this work, the environmental impacts of a PKS life cycle, ranging from the palm oil industry to its use as a fuel source in Japan power plants, are assessed. This opens up opportunities for biomass to break through the wall of uncertainty in biomass sharing schemes between resource exporting and importing countries. Import-dominant biomass power generation is environmentally encouraging compared with the local-dominant scheme, but dependent on careful selection of the biomass mix and power plant scale. Depending on the scenarios possible in the cradle-to-grave life cycle of PKS, the superiority and inferiority of such PKS-based power generation applications in Japan are interchangeable with life cycle GHG emissions. In any scenario case, exporting of PKS is economically beneficial for Malaysian oil palm sector where PKS used to be a waste. However, Japanese power suppliers will face future economic issues like risk of PKS price increase and the shifting from the imported resource to the domestic resources.

The replacement of PKS with EFB as the boiler fuel reduces the palm-based biomass in the POM and ensures availability of PKS. In this work, it is noted that LUC affected GHG emissions significantly. In particular, the conversion from peatland displayed excessive contributions to GHG emissions despite its low levels of conversion. Re-cultivation on degraded lands and conversion from non-profitable croplands are suggested. High WF values resulted from cultivation, while the POM operation accounts for a considerable percentage when POME treatment is considered. Eutrophication outcomes depended heavily on the levels of phosphorus in POME, stressing the importance of POME treatment. Environmental impact integration outcomes emphasized the huge influence of GHG emission on deciding the most and the least favorable scenario cases.

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Authors' contributions

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