Analysis of the human health damage and ecosystem quality impact of the palm oil plantation using the life cycle assessment approach

Khaled Obaideen1, Yong Chai Tan2, Pow Seng Yap3, Muhamad Awang4, Abdul Azim Abd Ghani5, Vijaya Subramaniam6 and Vin Cent Tai7

1Institute of Graduate Studies, Faculty of Engineering and the Built Environment, SEGi University.
2Centre for Modelling and Simulation, Faculty of Engineering and Built Environment, SEGi University.
3Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University Malaysia.
4Faculty of Environmental Studies, Universiti Putra Malaysia.
5Faculty of Computer Science and Information Technology, Universiti Putra Malaysia.
6Engineering and Processing Division, Malaysian Palm Oil Board.
7Centre for Modelling and Simulation, Faculty of Engineering and Built Environment, SEGi University.

Email: khaled.obaideen@gmail.com.

Abstract. In recent years the palm oil has been criticized because of its impacts on the environment and human health. Therefore, this study focused on the investigation of human health and ecosystem quality impacts that arose from the plantation of fresh fruit bunch of palm oil by employing an open-source software, namely OpenLCA version 1.5. The life cycle assessment approach was used for the analysis of the investigated impacts. The effects of land use changes on the human health and ecosystem quality were assessed. By employing ReCiPe Endpoint methodology in life cycle impact assessment phase the total ecosystems impact 0.00017 species per year while total human health damage was 0.00146 DALY. The results showed that the land use change has an impact on all the impacts categories except the freshwater eutrophication, freshwater ecotoxicity, ozone depletion, terrestrial ecotoxicity, and terrestrial acidification. In addition, the analysis showed that the application of the fertilizers and pesticides were the main contributor in all the impact categories. The results show that transportation is not the major contributor in any one of the impact categories.

1. Introduction

The United Nations launched a set of 17 Sustainable Development Goals (SDGs) in 2015 [1]. The palm oil industry has the great opportunity to assist in achieving these goals, especially in ending the poverty and hunger, promoting the economic growth sustainably, and addressing climate change. The palm oil can aid to end hunger by maximizing the land usage since it has the highest yield per hectare [2] and provides nutrients to billions of people in the world [3]. The growing palm oil industry has assisted in reducing poverty since a very significant amount of palm oil (around 40%) is produced by the smallholder [4]. In addition, the palm oil is mainly produced in the developing countries, in particular with its recent exploration in Africa [5].

A reasonable amount of literature has been covered the impacts of oil palm plantation on the environments and human health impacts [6,7] [8–10]. Most of those studies focused on greenhouse gas emissions and energy balances. Although some studies included other impacts, the impacts covered were not comprehensive. Additionally, most of the previous studies used paid software [8,11–13] such as GaBi and SimaPro. This shows...
that there is a need to analyse the environmental impacts of oil palm more comprehensively and understand the relation between the impact categories and oil palm plantation activists. By understanding this relation, the decision maker and oil palm manager will able to reduce their environmental impacts more effectively. This reduction should not only cover the climate change, but it should also cover the other environmental impacts. In addition, since around 40% [14] of oil palm is produced by the smallholders the free software needs should be utilized more. In the present study, a total of 15 impact categories were investigated utilizing the most recent ReCiPe Midpoint (version 1.11) Ecoinvent database, version 3.4. An open-source software, namely OpenLCA (version 1.5) was employed.

2. Methodology

Life cycle assessment (LCA) is the only standard, recognized internationally for estimating the environmental impacts of a product, process, or activity [15]. LCA gives decision-makers the ability to identify and quantify the environmental impacts of a product, process, or activity during its entire life cycle. The LCA results depend on the quality of the data provided in the life cycle inventory (LCI) [16]. LCI data in this study was obtained from two main studies, namely Zulkifli et al. [11] and Choo et al. [12]. These two studies were conducted by the Malaysian Palm Oil Board (MPOB) and with assistance from the Industrial Research Institute of Malaysia (SIRIM) and representatives of the stakeholders from the palm oil industry.

2.1. Goal and scope

This paper aims to analyze human health damage and ecosystem quality arise from the plantation of fresh fruit bunches (FFB) of palm oil.

2.2. Functional unit

The functional unit was based on 1 ton of FFB produced and land use change (LUC) assumption was based on a hectare.

2.3. System boundary and system characteristics

This system followed a cradle-to-gate approach. It starts with the land preparation and transferring of the seedlings from the nursery to plantation until the FFB are distributed to the mill.

| Included criteria | Excluded criteria |
|-------------------|-------------------|
| Manufacture of urea ammonium sulphate, phosphate rock, muriate of potash and plantation pesticides | Indirect land use change |
| Application of fertilizers, pesticides | Impact of heavy metals |
| Transportation | Manufacture of maintenance and replacement of capital equipment |
| Land use change | Manufacture of kieserite fertilizer, borate fertilizer, NPK compound fertilizer |
| Energy usage | Output to air, water, and soil |

2.4. Life cycle inventory (LCI)

The source of the data was from Malaysian Palm Oil Board (MPOB). The database used was the Ecoinvent version 3.4 database.

2.5. Life cycle impact assessment (LCIA)

Life cycle impact assessment (LCIA) is an essential phase in LCA. LCIA assists the decision-makers to quantify the emissions and resource consumption associated with product life cycle [17]. It is done by categorizing the inventory data into different impact categories. LCIA methods are classified into two main orientations or classifications, namely midpoint methods and endpoint methods. Endpoint is supportive for the decision-makers, while midpoint, is helpful when specific environmental concerns are targeted.
2.6. Sensitivity analysis and data quality analysis
Monte Carlo (MC) analysis was used to analyze the uncertainties in the LCIA. The parameters used in MC were based on the literature review [8,9,18–21].

3. Results and discussion

3.1. Life cycle inventory (LCI)
Table 3 shows the LCI used in the analysis. The impacts of the LUC are reported and discussed separately. Table 4 shows the main assumption used in this study.

| Flow                      | Amount | Unit | Flow                      | Amount | Unit |
|---------------------------|--------|------|---------------------------|--------|------|
| Sulfonyl urea             | 0.148  | kg   | Phosphate fertilizer      | 0.64   | kg   |
| Bipyridylum              | 0.104  | kg   | Phosphate rock            | 6.55   | kg   |
| Transport                 | 55.25  | t*km | Ammonium sulfate          | 8.05   | kg   |
| Nitrogen fertilizer       | 3.49   | kg   | Ammonium nitrate          | 0.76   | kg   |
| Phosphate fertilizer      | 2.8    | kg   | Dimethylamine             | 0.031  | kg   |
| Salt tailing from a potash mine | 11.6 | kg   | Potassium fertilizer     | 11.5   | kg   |
| Potassium fertilizer      | 4.5    | kg   | Diesel burned in agricultural machinery | 2.0145 | l |
| Urea, as N                | 0.41   | kg   | Organophosphorus          | 0.064  | kg   |
| Ammonium chloride         | 0.72   | kg   | Seedling                  | 0.33   | Item(s) |
| Pyrethroid-compound       | 0.0215 | kg   | Pesticide, unspecified    | 2.087  | kg   |
| Glyphosate                | 0.338  | kg   |                           |        |      |

Table 4 The assumptions used.

| Plantation characteristics |                        |
|----------------------------|-------------------------|
| FFB yield (ton/ ha⁻¹ yr⁻¹) | 20.7                    |
| Planting density (palm ha⁻¹) | 142                    |
| Soil characteristics       | Mineral soils           |
| Plantation lifetime        | 25 years                |
| No of plantations          | 102                     |

3.2. Life cycle impact assessment (LCIA)
Table 5 shows the LCIA results using ReCiPe Midpoint (version 1.11), and the impacts when the LUC was considered and the significant source of this impact. Fig. 1 indicates the relationship between FFB LCI parameters, significant flow contributors, midpoint indicator and endpoint indicator using ReCiPe [22]. This figure only shows the major flow contributors. The complete details are available in the supplementary information. In the following section, the results and discussion of each impact are presented. The results show clearly that changes will also lead to changes in the midpoint indicator and endpoint indicator.

| Impact category                      | LUC not accounted | LUC accounted | Major source of the impacts |
|--------------------------------------|-------------------|---------------|-----------------------------|
| Agricultural land occupation (m²a)   | 1.91              | 2.15          | Pesticide                   |
| Climate Change (kg CO₂ eq)           | 95                | 723           | Fertilizer                  |
| Freshwater ecotoxicity (kg 1,4-DB eq) | 28.9          | 28.9          | Fertilizer                  |
| Freshwater eutrophication (kg P eq)  | 0.024             | 0.024         | Pesticide                   |
| Human toxicity (kg 1,4-DB eq)        | 32.5              | 38.7          | Fertilizer                  |
| Ionizing radiation (kg U235 eq)      | 3.9               | 4.3           | Fertilizer                  |
| Marine ecotoxicity (kg 1,4-DB eq)    | 1.3               | 1.5           | Fertilizer                  |
| Marine eutrophication (kg N eq)      | 0.06              | 0.08          | Fertilizer                  |
| Natural land transformation (m²)      | 0.008             | 2.633         | Fertilizer                  |
| Ozone depletion (kg CFC-11 eq)       | 4.21E-05          | 4.31E-05      | Pesticide                   |
| Particulate matter formation (kg PM₁₀ eq) | 0.2        | 1.6           | Fertilizer                  |
| Photochemical oxidant formation (kg NMVOC) | 0.2 | 1.4           | Fertilizer                  |
3.3. Land use change impacts

Land competition is expected to continue to increase in the future for the palm oil plantation [23]. In this study, LUC was accounted independently. By doing that, the assumptions were reduced to the minimum. Table 6 provides details on the increase percentage when the LUC was included. The LUC accounted for the result of the carbon emission. Since natural land transformation impact is subjected to LUC [24], there are sharp increases in the value. The results indicated that LUC does not have any effects on the terrestrial ecotoxicity. The results also revealed that LUC has a very slight impact on freshwater eutrophication and freshwater ecotoxicity. Based on the results, the LUC influenced the ecosystem quality more than human health impact. The main impacts being resulted from the LUC were climate change, particulate matter formation, photochemical oxidant formation, ecosystems natural land transformation and the ecosystems-total. To reduce these impacts, the LUC should be reduced to the minimum.

Table 6 The additional percentage for LCIA when LUC was accounted.

| Impact category                                      | %    | Impact category                                      | %    |
|------------------------------------------------------|------|------------------------------------------------------|------|
| Agricultural land occupation (m²a)                   | 12.36| Ozone depletion (kg CFC-11 eq)                       | 2    |
| Climate Change (kg CO₂ eq)                          | 665  | Particulate matter formation (kg PM10 eq)            | 589  |
| Freshwater ecotoxicity (kg 1,4-DB eq)               | 0.13 | Photochemical oxidant formation (kg NMVOC)           | 559  |
| Freshwater eutrophication (kg P eq)                 | 1    | Terrestrial acidification (kg SO₂ eq)                | 3    |
| Human toxicity (kg 1,4-DB eq)                       | 19   | Terrestrial ecotoxicity (kg 1,4-DB eq)               | 0    |
| Ionising radiation (kg U235 eq)                     | 8.89 | Ecosystems-total (species*year)                      | 10377|
| Marine ecotoxicity (kg 1,4-DB eq)                   | 12   | Human Health-total (DALY)                            | 563  |
| Marine eutrophication (kg N eq)                     | 25   |                                                      |      |

3.4. The relationship between FFB LCI parameters and LCIA

To understand the relationship between FFB LCI parameters and LCIA, the LCI parameters were categorized into three main categories i.e transportation, fertilizer and pesticides, as shown in Fig 1. The analysis showed...
that transportation was main contributors of the following flow: radon-222, nitrogen oxides, ammonia, and phosphate. The fertilizer was the key contributors of the following flow: nitrogen oxides, occupation forest intensive normal, ammonia, phosphate, the transformation from forest intensive, metsulfuron-methyl, and occupation construction site. The pesticides were the key contributors of the following flow: methane, tetrachloro- r-10, radon-222, manganese, dinitrogen monoxide. Each of these flows contributed to at least one of the impact categories. It should be noticed a 2% cutoff was used to simplify the relationship.

3.5. Uncertainties and data quality analysis
The input values adopted were based on two main data from Choo et al. [12] and Zulkifli et al. [11]. The results of MC are presented in Table 7. This table demonstrates the major elements. A total of 1000 MC simulations were run in OpenLCA 1.5. The high coefficient of variation provides the evidence that the plantation of palm oil has a high uncertainty in most of the impact categories. More analysis should be done to determine the source of this high uncertainty. It can be noticed that ozone depletion has the highest uncertainty. This was because the ozone depletion influenced by the application of the pesticide. The lowest uncertainty was on freshwater ecotoxicity. The small value of the coefficient of variation in the climate change impacts suggested that the result has high accuracy. There is a similarity between this result, the climate change impact, and the result from Schmidt [25]. In general, the uncertainty can be explained because each study has different functional units, different LCIA methods, various system boundaries, and various locations.

| Impact category                  | Coefficient of variation | Uncertainty (%) | Impact category                  | Coefficient of variation | Uncertainty (%) |
|---------------------------------|--------------------------|----------------|---------------------------------|--------------------------|----------------|
| Agricultural land occupation    | 5.49                     | 549%           | Natural land transformation     | 1.61                     | 161%           |
| Climate Change                  | 0.18                     | 19%            | Ozone depletion                 | 13.3                     | 1331%          |
| Freshwater ecotoxicity          | 0                        | 1%             | Particulate matter formation    | 0.28                     | 28%            |
| Freshwater eutrophication       | 6.79                     | 680%           | Photochemical oxidant formation | 0.61                     | 62%            |
| Human toxicity                  | 0.52                     | 52%            | Terrestrial acidification       | 0.11                     | 11%            |
| Ionizing radiation              | 4.41                     | 441%           | Terrestrial ecotoxicity         | 0                        | 0%             |
| Marine ecotoxicity              | 0.25                     | 26%            | Ecosystems-total               | 0.11495                  | 11%            |
| Marine eutrophication           | 0.35                     | 36%            | Human Health-total             | 0.247014                 | 25%            |

4. Conclusion
The palm oil industry can assist in achieving the 17 Sustainable Development Goals. The results obtained using an open-source software were consistent with other research findings, thus this proved that smallholders can use these results, but have to adjust according to its data. The analysis showed the total ecosystems impact 0.00017 species per year while total human health damage was 0.00146 DALY. A detail relation between oil palm plantation activities, major flow contributors, midpoint indicator, endpoint indicator, and the impact was identified as shown in figure 1. The results could be used by the decision maker to determine ways to reduce human health damage and ecosystem quality from their oil palm plantation. The main focuses should be in reducing the application of the fertilizers and pesticides. While the transportation should be given the lower focuses because it has a lower impact in comparison with other activities. Because 16 impacts were covered, this would also give the decision maker the ability to avoid increasing the other impacts while trying to reduce one. When LUC was included, the results significantly changed in most of the impacts categories. The uncertainties analysis showed that the results were dependent on the values adopted in the LCI, especially pesticides and fertilizer values.

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