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Life-Cycle Environmental and Cost Analysis of Palm Biomass-based Bio-Ethanol Production in Malaysia

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The palm oil industry generates a high amount of residues during their processing. Empty fruit bunches (EFB) is one of the biomass which can be utilised for bioethanol production. In this study, life cycle assessment (LCA) with the cradle-to-gate approach is performed with the help of SimaPro version 9.0, whereby four impact categories are evaluated. The economic performance of the production is analysed through life cycle costing (LCC). The scope is from palm tree cultivation to refined bioethanol production. In LCC, specific cost data such as raw material costs, labour and capital expenditure, operational costs, and transport costs will be considered. The LCC is 562.44 MYR/t of bioethanol with an annual profit of 5.50×10^8 MYR/y and a payback period of 0.51 y. From an environmental view, the significant contributors to the environmental impacts are agriculture and the pretreatment process. From an economic perspective, the chemical cost is the most burden cost in the upstream process. In contrast, the cost of the raw materials is the main contributor to the bioethanol production cost. The environmental impacts and cost burden can be reduced by cutting down the usage of chemicals.

1. Introduction

Malaysia is the second-largest exporter of palm oil products after Indonesia, which had about 452 palm oil mills with a total processing capacity of 112.91×10^6 t/y of fresh fruit bunch (FFB) (MPOB 2020). The palm oil industry generates a significant amount of biomass waste, accounting for 85.5 % of total biomass production in Malaysia (Phang and Lau, 2017). The palm oil residues of solid waste have a large volume of 5.5-8 % palm shells, 20-23 % empty fruit bunch (EFB), and 15 % palm fibre from FFB (Mohd Yusof et al., 2019). EFB can be utilised as a biofuel because of its high cellulose and hemicellulose (Derman et al., 2018). Based on Derman et al. (2018), the cellulose and hemicellulose in the EFB is promising feedstock for bioethanol production. It can be chemically hydrolysed to glucose by enzymatic or acid and then is required for the fermentation to produce bioethanol. Bioethanol utilisation as biofuel can pave the way for cleaner earth together with less dependency on fossil fuel. Chiew and Shimada (2013) carried out a life cycle assessment (LCA) to analyse and compare the environmental impact of different technologies to convert EFB to fuel, fibre and fertiliser. Do and Lim (2016) only focus on comparing the most economically feasible pathway among three energy conversions from EFB to bioethanol, combining heat and power and hydrocarbon. The studies do not discuss the environmental impacts on the conversions. In Brazil, techno-economic and LCA of biorefineries based on EFB to cattle feed and ethanol were conducted by Vaskan et al. (2018). The LCA and LCC of bioethanol production from EFB in Malaysia must be studied to identify the associated environmental issues and economic feasibility. This study aims to conduct LCA and LCC to evaluate environmental and economic performance for bioethanol production from EFB, considering its upstream processes. The study identifies the significant environmental hotspots and the cost categories that cause the most economic burden to the processing system. The potential mitigation plans are also discussed in this study.

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2. Methodology

LCA is an evaluation tool to determine the environmental impact of a product or service over its entire life cycle (Gnansounou et al., 2015). In the current study, LCA methodology is guided by ISO 14040, and ISO 14044 (ISO, 2006) is applied to analyse environmental impacts and identify the significant environmental hotspot. The Life Cycle Cost (LCC) summarises the total cost of a product that includes raw material, operation, and capital investment. LCC aims to analyse economic performance by identifying and quantifying all the necessary costs involved during the life cycle of bioethanol production from EFB.

2.1 LCA

The ISO standards define four basic steps, namely (i) goal and scope definition; (ii) inventory analysis; (iii) impact assessment; and (iv) interpretation.

2.1.1 Goal and scope definition

The main goal is to evaluate the environmental impact of bioethanol production from EFB. The functional unit of 1 t bioethanol produced is selected for cradle to gate system boundary. The scope of this study includes agriculture and transportation stages of EFB and biochemical conversion of EFB into bioethanol. The palm oil extraction process is not measured within the boundary of the EFB since the main goal is to generate bioethanol. The crude palm oil (CPO) extraction process and bioethanol end-use in vehicles are excluded from this study. The life cycle inventory (LCI) data to produce EFB is allocated based on the economic value of EFB and palm oil fruits (Gnansounou et al., 2015). The environmental impacts from nursery and plantation stages are allocated to EFB based on the monetary value, which is 1.67 % (Reeb et al., 2014). Figure 1 shows the system boundary for bioethanol production and significant input and output to the system.

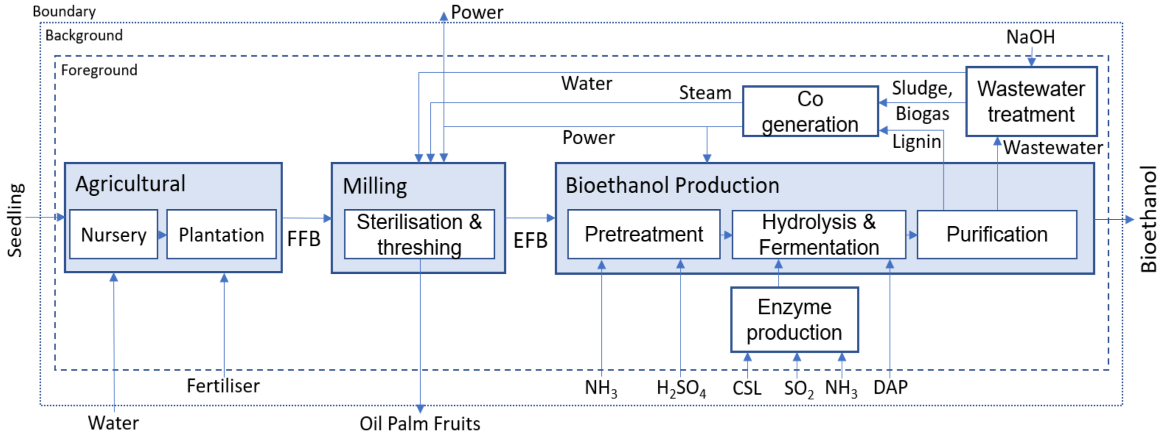

Figure 1: System boundary for production of bioethanol

2.1.2 Process description and life cycle inventory (LCI)

The production of bioethanol is divided into three stages: agricultural, milling and bioethanol production. The agricultural stage comprised of two sub-stages, namely the nursery and plantation stage. The germinated oil palm seedlings are grown in polybags in the pre-nursery stage. Later, four-month-old oil palm is transferred to big polybags for 12 mths of cultivation with sufficient water (1.5-2 L per polybag per d) and then transferred to the plantation (Halimah et al., 2010). The transportation usage is 1.43×10^{-6} tkm. It is estimated that one seedling can produce 4.538 kg of bioethanol. The average plant density is 142 plants/ha and has 20.14 t/ha of FFB in the year 2020 in Johor state (MPOB, 2020). In this current study, the amount of fertiliser, herbicide and pesticide application in the agricultural stage is according to Reeb et al. (2014), which based on 20.7 t/ha of FFB harvested annually. The life span of the oil palm trees is assumed to be 25 y. Finally, the harvested FFBs are transported to the nearby palm oil mill via trucks (Zulkifli et al., 2010). The total transportation for transferring FFB, fertiliser, and pesticides to the plantation amounts to 1,450 tkm. Sterilisation and threshing processes are the two only processes considered in the milling stage. Steam passes through the steriliser, which helps to loosen the individual fruits from the stalk or bunch. The sterilised FFB are then sent to the threshing station to separate fruits from the stalks or bunches to be EFB. Threshing process outputs are 23 % EFB, and 77 % of fruits continued to palm oil extraction. The electricity usage for sterilisation and threshing is 2.09 kWh/t FFB. The EFB is later transported to biorefinery which the distance is assumed 30 km, which is 0.181 tkm.

179 MJ/t bioethanol of electricity is consumed to chip and mill the EFB into smaller size in pretreatment. The EFB is then hydrolysed by dilute fill with 9.03 kg H_2SO_4 /t EFB added to catalyse the hydrolysis process. All the pre-treated EFB is fed into a conditioning reactor where an aqueous solution of ammonia (NH_3) and water with 8.18 kg NH_3/t EFB and 853.72 kg water/t EFB are injected for pH control. After pretreatment, the diluted conditioned EFB is conveyed to separate the hydrolysis and fermentation (SHF) process. A quantity of 60.51 kg of the enzyme is generated on-site that is used in enzymatic hydrolysis. In this process, enzyme bioreactors are loaded with glucose as a carbon source, water and nutrients, including steep corn liquor (CSL), NH_3 and sulphur dioxide (SO_2) (Vaskan et al., 2018). After 3.5 d, 90 % of the cellulose is converted into glucose, and the hydrolysed EFB is fed to the fermenter reactor for fermentation. CSL and diammonium phosphate (DAP) are both nitrogen sources for *Zymomonas mobilis* bacterium used for fermentation. 95 % of glucose and 85 % of xylose fractional conversions to bioethanol are assumed (Vaskan et al., 2018). The fermentation broth is fed to a purification facility comprised of a beer column and rectification column. First, the beer column is used to remove the dissolved CO_2, and most of the water and its bottom stream contains lignin and wastewater. The wastewater is directed to wastewater treatment (WWT) for clean-up. The bioethanol is then condensed in the rectification column. Every t of FFB is found capable of producing 38.13 kg of bioethanol, based on the assumptions from Goh et al. (2010). The lignin from the purification process, biogas from anaerobic digestion, and biomass sludge from WWT are burned at the boiler in cogeneration. A multistage turbine and generator are used to generate electricity. The total power generation from the cogeneration is determined based on Vaskan et al. (2018), assuming the efficiency is 75 % and 30 % of heat loss. A total calculated of 2.40 $\times 10^5$ MJ/h of power is generated from the system. The process uses 2.31 $\times 10^5$ MJ/h, leaving about 8.93 $\times 10^3$ MJ/h to be sold to the grid.

2.1.3 Life cycle impact assessment (LCIA)

The assessment is performed using the ReciPe Midpoint (H-hierarchist version) is applied (Vaskan et al., 2018). The impact categories studied are global warming, terrestrial acidification, freshwater eutrophication and freshwater ecotoxicity. The emissions from infrastructure and capital are not in the scope of the study as the primary aim is to assess the impacts on the environment and economics. This LCA study only applied classification and characterisation without considering the normalisation and weighting phase.

2.2 Life cycle costing (LCC)

LCC is performed to assess the economic analysis by considering all the cost factors related to the life cycle of the EFB biorefinery studied for bioethanol production. The cost of bioethanol production is estimated from specific cost data, such as raw material costs, labour and capital expenditure, operational costs, transport cost. Similar system boundary and assumptions as used in the LCA study are applied in LCC. The LCC for 1 t bioethanol is calculated using Eq (1) (Soam et al., 2018).

$$LCC_{bioethanol} = \left(FC_{annual} + Cap_{annualized} + OC_{annual} - C_{surplus\ electricty}\right)/bioethanol\ production \quad (1)$$

Where $LCC_{\ bioethanol}$ denotes life cycle cost of 1 t of bioethanol, FC_{annual} is the annual feedstock cost, $Cap_{annualized}$ is the annualised capital cost, OC_{annual} is the annual operation cost, and $C_{surplus\ electricty}$ is the annual operation benefits gain from surplus electricity. The annual profit and payback period are then calculated.

2.3 Data collection

The oil palm plantation data collected are mainly sourced from the Malaysia Palm Oil Board (MPOB) official reports, journal articles, and databases from SimaPro software. The biomass-based bioethanol plant is not installed in Malaysia. The data is collected from journals articles and the SimaPro software database. According to the current study plant capacity, the collected data are converted based on the functional unit.

Plantation costs are collected from journal article from independent smallholder plantations in Johor, Malaysia (Ismail et al., 2003). Economic allocation of 1.67 % is applied to obtain EFB cost because EFB is a co-product of FFB. Due to the lack of the latest data for the production cost of FFB, the cost is adjusted for inflation to base-year 2019 with an average inflation rate of 2.16 % (Macrotrends, 2021). The cost items are categorised into six groups as follows (1) seedling cost (2) upkeep cost (3) chemical purchase (fertiliser, herbicide and pesticide) (4) harvesting cost (5) transportation (in-field transportation and transfer of FFB to the mill) and (6) other costs including other expenses and land quit rent is based on the quit rent rate of 0.18 RM/m^2. The electricity cost in the milling stage and the machine price of steriliser and thresher are included in the production cost of FFB.

The cost of bioethanol is contributed by (1) feedstock cost, (2) operation and maintenance including labour, chemicals, insurances and taxes, maintenance, plant overhead, administration cost, selling expenses, research and development, depreciation, and transportation, (3) capital cost including machinery and equipment, consultant fee, land cost, construction fee, pro-retable expenses, filed expenses and project contingency, (4) revenue from surplus electricity generation. The equipment sizing and capital cost are collected from Vaskan et al. (2018) and Do et al. (2015). The surplus electricity is sold according to the concept of Net Energy Metering. The capital cost annualisation is performed by calculating the equivalent annual cost. Meanwhile, the economic assessment considers a project lifetime of 25 y and an annual interest rate of 10 % (Do et al., 2015).

3. Result and discussion

The environmental impact of bioethanol production through LCA methodology is illustrated in Figure 2. Pretreatment and enzyme production processes are the most significant impact categories. The plantation stage significantly impacts freshwater eutrophication. The impact on freshwater eutrophication (9.4 %) mainly comes from phosphorus fertiliser and pesticide during the plantation operations, leading to phosphate and phosphorus emissions to water. The plantation stage has also contributed 5.4 % of total global warming due to the high use of fertilisers and pesticides in oil palm plantations. A large amount of electricity is required to produce chemicals and pesticides. Thus a large amount of fossil fuel is burned to generate electricity, mainly contributing to greenhouse gas (GHG) emissions. The necessary use of fertiliser and pesticide leads to the emission of nitrogen oxides (NO_x), ammonia (NH_3) and sulphur dioxide (SO_2), which result in terrestrial acidification and freshwater ecotoxicity.

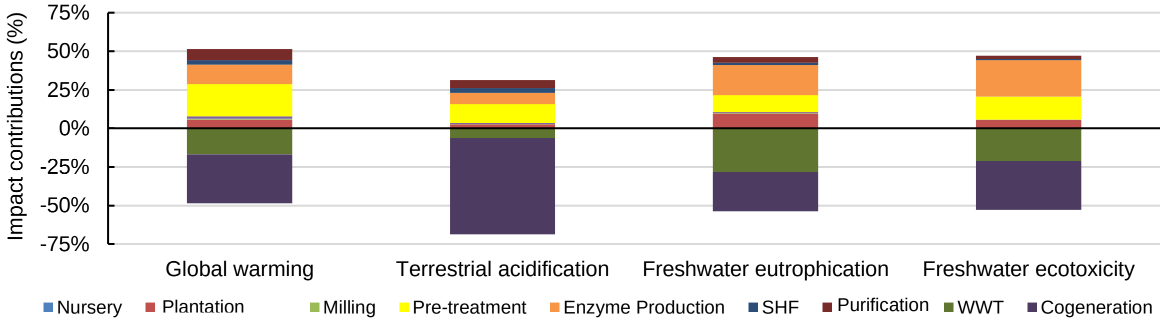

Figure 2: Environmental impact of bioethanol production

The oil palm tree nursery has a low and insignificant impact on the environment because the required inputs are relatively low. Bio-fertilisers, such as Plant Growth Promoting Rhizobacteria (PGPR) (rhizo-biofertilizers), are eco-friendly alternatives to hazardous chemical fertilisers in the agricultural stage. It is an efficient soil microbe for sustainable agriculture and increases yields by significantly decreasing the number of pesticides and chemical fertilisers used (Basu et al., 2021). Pretreatment and enzyme production in biorefinery plant show significant impact among the impact categories. H_2SO_4 and NH_3 used in the pretreatment and enzyme production stage are primarily responsible for greenhouse GHG emissions in the bioethanol production chain, representing 20.9 % and 12.7 % for pretreatment and enzyme production. Production of NH_3 by the Haber-Bosch process has the disadvantages of high GHG emission and high amount of energy usage due to high operating pressure and temperature. Sustainable NH_3 production by adopting water electrolysis coupled with renewable technology such as wind and solar energy to produce hydrogen can reduce GHG emissions (Ghavam et al., 2021). Industrial H_2SO_4 and NH_3 production are the primary sources for NH_3 and SO_2 emissions to the air. A reaction of these released gases to the air could take place with water from the atmosphere and produce sulphur and nitrogen-based acids precipitating as acid rain. As the acid rain flows through the soil, it could leach aluminium from soil clay particles and then flow into streams and lakes, leading to freshwater ecotoxicity (Gandhi and Diamond, 2018). The purification process contributes to 7.1 % of global warming because it is considered an energy-intensive process (Ebner et al., 2018). Wastewater generated from purification consisted of pollutants, including soluble fermentation residues, leading to terrestrial acidification (10.2 %). Carbon released in bioethanol plant is from biomass and is considered biogenic. Biogenic carbon dioxide emission has a global warming potential of zero. Figure 2 shows the negative value (positive impact) of WWT and cogeneration since the WWT plant, and cogeneration system is designed in the biorefinery plant. The cogeneration system is used to recover the waste stream, such as filtrate, lignin, sludge, and biogas. A positive environmental impact could be observed if a specific treatment plant is performed on the waste stream generated from the biorefinery plant itself (Poveda-Giraldo et al., 2021).
LCC analysis discussion is divided into two major parts: the nursery and plantation (agricultural) and the bio-ethanol production. The three highest cost items that contribute to the cost of plantation stage are land cost (78.3 %), land quit rent (6.6 %), and fertiliser (6.1 %). Land cost and land quit rent are unavoidable cost that

must be paid to local authorities each year. The need for fertilisers for oil palm growth is high. Various fertilisers are required to apply in the oil palm plantation, leading to a high purchase cost of fertilisers. Fertiliser usage should be minimised to reduce the cost of fertiliser application. Ammonium sulphate, ammonium nitrate, ammonium chloride and urea are common fertilisers used as the sources of nitrogen in the plantation. Tarmizi and Mod Tayeb (2006) suggested that the application of 4.2 kg /(tree*y) of ammonium sulphate managed to produce 30 t FFB/ha. The application of ammonium sulphate alone is sufficient for the oil palm tree. The total production cost is 2,134.36 MYR/t of FFB, while the cost can be allocated to 37.56 MYR/t of EFB.

The EFB cost is the dominant cost factor in bioethanol production; it represents 49.2 % of the significant cost related to the bioethanol plant. The EFB cost is interrelated with the production of FFB, whereby the production cost of FFB can be reduced by decreasing the usage of fertilisers. A combination of reducing plantation cost (fertilisers purchase and application) and increasing yield will be a practical way to reduce the EFB cost (Nguyen et al., 2008). Transportation cost for EFB from milling stage to biorefinery plant is the second-highest cost contribution (33.1 %) to bioethanol production. The EFB transportation cost from milling to biorefinery is calculated based on a standard industry value for transport cost in Malaysia of 0.7166 MYR/tkm, which 30 km distance is assumed (Reeb et al. 2014). The transportation cost is mainly due to the fossil fuel cost. Biofuel can be an alternative way to use zero value waste for feedstock as a resource for low-cost biofuels (Karmee and Lin, 2014). Besides, the machinery and equipment also affect the bioethanol production cost, representing 5 % of the total cost of bioethanol production. The machinery and equipment cost could be reduced by running a utilisation report that shows each piece of equipment's utilisation against its target or budgeted hours. 20 - 25 % of surplus equipment could be reduced after running the report (Ingalls, 2009). The surplus electricity from the cogeneration plant is sold to the grid to obtained extra revenue for the bioethanol production plant. The revenue of the bioethanol process is assumed at 2,400.27 MYR/t (Trading Economics, 2021) and electricity at 0.355 MYR/kWh (peak) and 0.219 MYR/kWh (off-peak) (TNB, 2021). In this study, the bioethanol production is 299,191.33 t/y, and the LCC is 562.44 MYR/t of bioethanol. It is found the process can have an annual profit of 5.50×10^8 MYR/y and a payback period of 0.51 y. The low payback period found because bioethanol revenue is very high compared to the EFB price. The EFB is a waste from the existing palm oil industry, which allocation has been done for the upstream processes, and the cost for EFB become cheap. The biomass waste in the bio-ethanol plant has also been considered for energy recovery to cover the costs.

4. Conclusion

The environmental impacts of bioethanol production from EFB is studied in this study, followed by possible solutions suggestions for lowering the environmental impacts. Among all the impact categories, global warming has the highest impact (51.4 %), followed by freshwater ecotoxicity (47.2 %), freshwater eutrophication (46.3 %) and terrestrial acidification (31.3 %). Major contributors to these impact categories are agricultural and pretreatment due to the fertiliser and chemicals used. The positive environmental impact could be observed with the design of WWT and cogeneration system in the biorefinery plant. Fertiliser contributes the highest cost in the agricultural stage, and raw materials are the highest cost in the biorefinery plant. The LCC is 562.44 MYR/t of bioethanol with a profit of 5.50×10^8 MYR/y and a payback period of 0.5 y. The EFB as waste from palm oil production has a low cost to the process, compared to the revenue from the bioethanol. In addition, the energy recovery from process waste helped to improve the financial feasibility.

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