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Life cycle assessment to evaluate the green house gas emission from oil palm bio-oil based power plant

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Abstract−The objective of this study is to assess the green house gas (GHG) emission for the production of bio-oil from oil palm biomass and its utilization for 10 MW power generation by evaluating the life cycle carbon footprint analysis. The life cycle GHG emission assessment includes four main stages, which cover the oil-palm cultivation, palm oil mill operation, biomass transportation and pyrolysis process for the production of bio-oil and its utilization for 10 MW power generation. The results obtained suggest that the palm bio-oil has potential as a carbon neutral renewable energy source in the future. More importantly, it has no negative impact on the environment as the amount of CO_2 emitted to the atmosphere during combustion of this fuel is lower than that of the CO_2 absorbed from the atmosphere during cultivation stage.

Key words: Life Cycle Analysis, Carbon Footprint, Bio-oil, Pyrolysis, Oil Palm Biomass

INTRODUCTION

Currently, most of the energy demand is satisfied by fossil fuels such as natural gas, petroleum, and coal. However, fossil fuel burning for energy production is not sustainable in terms of climate change and energy security. The extensive use of fossil fuels causes a huge accumulation of greenhouse gases (GHG) into the atmosphere which in turn causes global warming and other environmental problems [1]. Therefore, there is an urgent need to replace fossil fuels with renewable, sustainable and environmental-friendly sources in order to create a sustainable future. There are a number of renewable energy resources currently being considered to utilize in large scale such as biomass energy, solar energy, wind energy, geothermal energy, and hydropower. However, the utilization of most of the renewable energy is not economically and technically viable. For example, although solar energy is truly renewable and sustainable, it is high-tech process and still beyond the affordable range for large scale application [2].

Biomass is a renewable energy source derived from green plants and abundantly available. As a world leading palm oil producer, Malaysia produces huge amount of oil palm biomass which has great potential as a renewable energy source. Throughout 4.48×10^4 km^2 plantation area in Malaysia, about 87.7 tons of fresh fruit bunch (FFB), 11 tons of fronds and 3 tons of trunks per hectare are harvested in a year [3]. More than 400 palm oil mills are operated to produce palm oil (CPO) and palm kernel oil [4], which generate palm wastes of about (12-15%) fibers, (6-7%) shells, and (21-23%) empty fruit bunches (EFB) based on FFB [3,5,6]. These biomasses have inherently high energy content, which can be exploited using modern technologies, for example, pyrolysis process.

Most of the oil palm biomass (especially the EFB) is neither utilized for energy production nor converted to value added products due to the lack of proven technology. EFB is usually sent back to the plantation area for mulching and because of its excessive amounts; some of it is being disposed of in landfills, causing waste management and environmental problems. The landfill area produces a huge amount of methane gas. A large body of evidence shows that EFB biomass has high energy content, almost the same as hard wood and can be used as a renewable energy feedstock [7]. Palm kernel shell (PKS) is one of the high carbon density solid materials which is currently used as a combustion boiler fuel with very limited efficiency.

Pyrolysis is a promising technology that can be used to convert the abundantly available EFB and PKS biomass into a useful form of energy. In practical application of oil palm biomass via pyrolysis, two utilization philosophies can be implemented. First, pyrolysis of EFB and PKS can be carried out at the mill's premises and the liquid bio-oil can be transported to the centralized downstream application unit for producing chemicals, transportation fuel or electricity. Second, biomass can be transported to the centralized downstream application unit where it can be pyrolyzed and the product bio-oil can be used as a fuel for power generation. Since oil palm biomass is renewable, sustainable, abundantly available and cheap, its usage via the production of bio-oil as fuels and chemicals can reduce the land use for EFB disposal and the additional GHG emissions.

Despite the great probability for reducing GHG emission using oil palm biomass, the GHG emission is increasing due to the expansion of the oil palm plantations [8]. About 13 Mt y^{-1} of GHG is emitted from oil palm cultivation with an increase of 29% from the year 2000 [8]. The main contributors of GHG emission from palm oil industry are land conversion (60%), palm oil mill effluent and landfill area via anaerobic digestion (13%), fossil-fuel combustion (13%) and utilization of fertilizers (4%) [4]. In Malaysia, most of the land is covered with forests which are being cut down and oil palm is being replanted. During this activity, the land needs to be

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prepared, and this contributes a significant amount of carbon emission. However, there is a regulation known as Roundtable on Sustainable Palm Oil (RSPO) that controls the oil palm plantations and palm oil mills in Malaysia. The policy urges planters to make whole oil palm cultivation and palm oil production carbon neutral. As RSPO regulation, the carbon footprint from the land use and other activities is mandatory to be mitigated by other means. This clearly points the finger to the waste generated from the oil palm activities to be managed in a way which can contribute to mitigating the carbon footprint.

The Malaysian government has made a policy of zero-burning activity in the plantation area, which further urges finding some alternative utilization of oil palm biomass throughout the whole life of oil palm trees. Even at the end of whole life cycle of the oil palm tree, there is an enforcement law made in 1989, that replanting is mandatory. The oil palm trunks are simply shredded and placed back to the field as mulch.

In this LCA study, the environmental aspects and potential impacts (in terms of GHG emissions) of palm bio-oil production for power generation from cradle to grave are analyzed and assessed. The calculations are based on 10 MW power generation from palm bio-oil.

METHODOLOGY

1. Goal and Scope Definition

Life cycle assessment (LCA) on the carbon footprint of a product is a methodology to evaluate environmental impacts, carbon balance, greenhouse gas emission and other impacts for an entire system from the production to the disposal for the product. The standard of LCA study is developed and published by the International Organization for Standardization (ISO 14040-14049), which has been followed in this study. The objective of this study is to assess the GHG emission, which eventually produces in the entire system of the production of bio-oil from oil palm biomass and utilization of bio-oil for power generation. A number of stages are involved in the system that causes the GHG emission such as oil palm cultivation, transportation, oil mill operation, pyrolysis plant and the combustion of bio-oil in the electricity generation system. The GHG assessment was conducted to calculate the annual carbon dioxide (CO_2) emission from a 10 MW power generation plant by using bio-oil via pyrolysis process. All the calculations were done based on the energy coefficient reported in the literature [9] as briefly described in subsequent sections. Thus, the sustainability of bio-oil production for power generation in terms of carbon footprint is assessed.

2. System Boundary

The system boundary for palm bio-oil production and its utilization to produce 10 MW power is shown in Fig. 1. The production consists of four main stages: the cultivation of oil-palm stage, palm oil milling stage, the pyrolysis stage and finally, the power generation stage. The analysis excluded the assessment of gas emission related to the facilities construction, palm oil mill effluent (POME) treatment, mill and plant maintenance and manual labor [4].

In this study, all the calculations of the feedstock are based on EFB and a certain fraction of PKS as the raw materials and the basis of this analysis is based on the production of 10 MW power by using

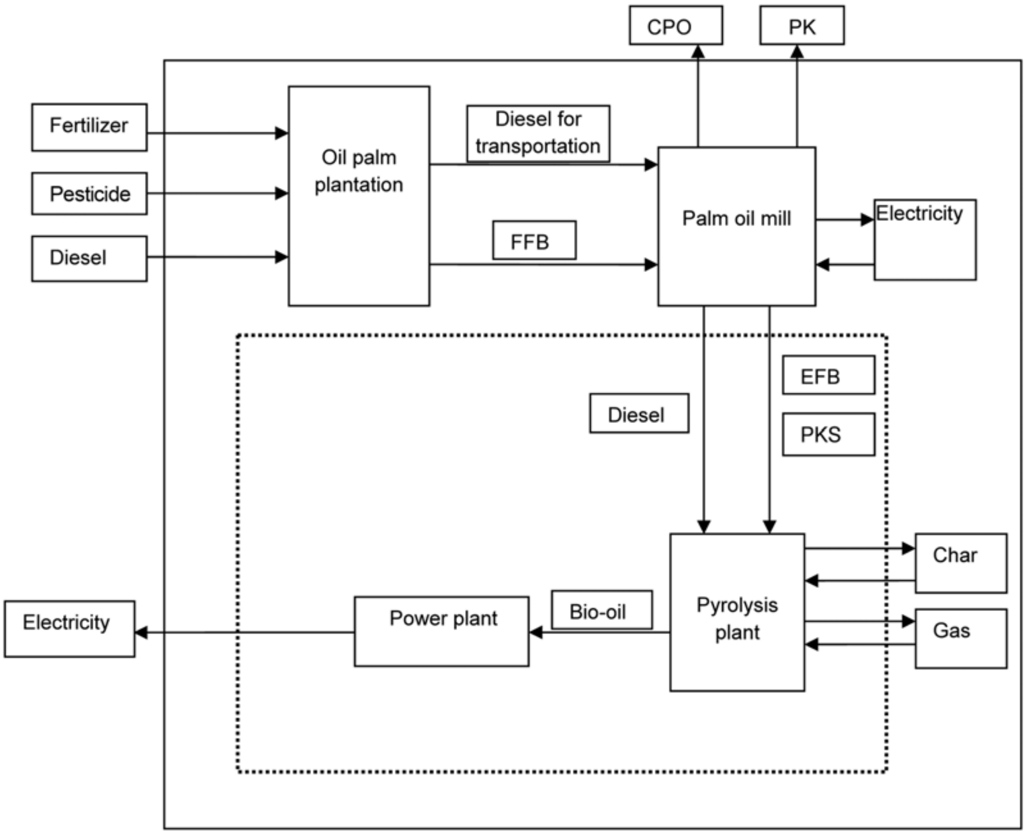

Fig. 1. System boundary for the production of bio-oil from oil palm biomass and electricity from bio-oil.

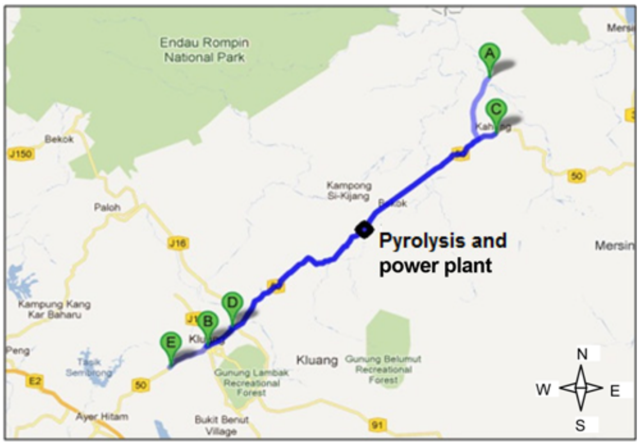

Fig. 2. Location of palm oil mills with the proposed pyrolysis and power generation plant.

Table 1. Distance from palm oil mills to pyrolysis and power plant [10]

	Palm oil mill	Distance (km)
A	Kilang Kelapa Sawit Sungai Kahang	90
B	Kahang Palm Oil Mill	75
C	Kilang Sawit Nitar	82
D	Kahang Palm Oil Mill	65
E	Kilang Kelapa Sawit Pamol	87
	Average distance	86
	Average round trip distance	172

Table 2. Production at plantation area

Production	Capacity ($t\cdot ha^{-1}\cdot y^{-1}$)
FFB	87.7
Trunks	3
Fronds	11

Table 3. Soil carbon content of different forest/tree types

Types of soil	Soil carbon content ($t\cdot ha^{-1}$)	Source
Tropical peat forest	1600	[16]
	3770	[17]
Tropical primary forest	120	[12]
	60	[18]
Tropical secondary forest	67	[19]
	62	[20]
Grassland	80	[20]
	40	[21]
Degraded land	1	[22]
Oil palm plantation	72	[23]

bio-oil in Taman Kahang, Kluang (in Johor state, Malaysia). The location of pyrolysis and power plant is shown in Fig. 2 [10]. Five palm oil mills are under operation in Kluang and the names and distance of palm oil mill from the central plant are mentioned in Table 1. The mills were selected based on the shortest possible distance. The entire mesocarp fiber and a certain fraction of PKS are considered to be used as a boiler fuels for steam generation for sterilizing FFB and producing mill's own power. The entire EFB and a fraction of PKS are proposed to be transported to the central unit.

3. Inventory Data

3-1. Oil Palm Cultivation and Harvesting

In the cultivation stage of oil palm, the emission from the land use change, pesticide and fertilizer from 0 to 25 years lifespan of oil palm is taken into account. The stage includes all processes such as nursery establishment, site preparation, field establishment, field maintenance, harvesting, collection and replanting. A fresh fruit bunch (FFB) can be harvested after 3-4 years of planting with a frequency of around 10-15 days or 2-3 times a month until 20 years of planting [11]. From 20 to 25 years, the harvesting rate obviously decreases and after 25 years of age it completely stops the reproduction. Then the replanting process usually takes place after trunk shredding and re-use as mulch in the field [12]. The production rate of FFB along with trunk and frond in Malaysia is shown in Table 2 [3]. From a backward calculation to produce 10 MW electricity from bio-oil, about 7.0×10^{2} $t\cdot d^{-1}$ FFB is needed to be processed, which eventually produces around 88 $t\cdot d^{-1}$ dry EFB and PKS. Considering the efficiency of the pyrolysis unit and electricity generation, the energy content in 88 $t\cdot d^{-1}$ biomass can produce 10 MW electricity.

The emission from fertilizer and pesticides is calculated based on the total amount used as the average of 9 months at the nursery stage and 25 years at the field stage. The emission related to fertilizer is mainly during the fertilizer production stage. The fertilizers used in the oil palm plantations were N-fertilizer 7.79 $kg\cdot t^{-1}$ of FFB, P_2O_5-fertilizer 0.05 $kg\cdot t^{-1}$ of FFB and K_2O-fertilizer 14.41 $kg\cdot t^{-1}$ of FFB [13]. The herbicides used in this study are glyphosate and paraquat. Glyphosate and paraquat are used as herbicides with an average of 1-3 times per year of glyphosate (0.28 $kg\cdot t^{-1}$ FFB) and paraquat (0.10 $kg\cdot t^{-1}$ FFB) as reported [13].

To determine the GHG emissions caused by land use change, five different types of soil used by Malaysian oil-palm plantations were modelled including peat forest, primary forest, secondary forest, grassland and degraded land [8]. It is presumed that some of the carbon is released when converting the forest to oil palm plantation. The carbon content in various type of soil per hectare of land is given in Table 3 [4,14]. Carbon exists in soil in two forms, inorganic and organic. Inorganic carbon exists as carbonate, e.g., calcium carbonate. During land use, the carbonate materials are exposed to sunlight and decompose to carbon dioxide. On the other hand, organic carbons exist in the soil as organic materials, which usually improve the soil quality by holding nutrients, water and also by buffering the soil. These organic materials decompose during land use by bacterial action as well as by thermal degradation to produce carbon dioxide. The inventory data consists of amount of GHG emissions through land use change, fertilizers and pesticides usage for whole palm oil planting and harvesting [15].

Thus the GHG emission for oil palm cultivation is determined by using the following equation:

$$\Delta M_{CO_2\,Oil\,palm\,cultivation} = (M_{CO_2\,Respiration} + M_{CO_2\,fertilizer} + M_{CO_2\,pesticide} + M_{CO_2\,landreclamation}) - M_{CO_2\,Photosynthesis} \quad (1)$$

where ΔM represents the net emission of CO_2 in oil palm cultivation and M defines CO_2 consumption and release in an individual

Table 4. Product distribution at milling stage

Product	Amount ($t\cdot ha^{-1}y^{-1}$)
Crude palm oil (CPO)	15.78
EFB	21.04
Palm kernel shell	5.20
Palm mesocarp fiber	11.40

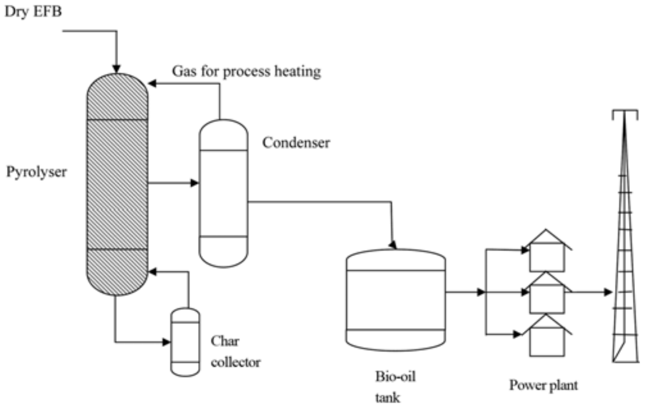

Fig. 3. Conceptual design of a pyrolysis and power plant.

process.

3-2. Palm Oil Mill

After harvesting, the FFB is transported within 24 hours to the palm oil mill to extract the oil in order to produce crude palm oil (CPO) as the main product and palm kernel (PK) as the co-product. The fresh fruit bunch must be transported to the mill and processed within 24 h to prevent enzymatic conversion of oil to free fatty acid. The palm oil mill is usually located near the plantation area in order to maintain the quality of the product. The milling process takes about 5.2 tons of FFB to produce one ton of CPO. The output of this stage includes CPO (15-18%), shells (5-6%), kernels (5-6%), palm fiber (12-14%) and empty fruit bunches (23-25%) as shown in Table 4 [24]. FFB processing to CPO involves six individual processes, which are fruit bunch sterilization, bunch threshing, fruit digestion, pressing, clarification and centrifugation, and nut drying, cracking, and kernel recovery [15]. Each of the stages involves energy and the generation of which emits significant amount of green house gases.

Heat and electricity used in the palm oil mill are mostly obtained from the burning of entire palm fiber in the boiler. About 90% electricity is generated by steam turbine installed in the mill while the rest (10%) is sourced from the national grid [15]. As reported in previous study, the total electricity used by machines in the mill is estimated to be 17.88 $kWh\cdot t^{-1}$ of FFB [13]. The rest of the palm waste, which includes palm kernel shell and EFB, is collected and assumed to be sent to pyrolysis and power plant to be utilized [5]. To calculate total GHG emission in palm oil mill, the following equation is used:

$$\Delta M_{CO_2\ Palm\ oil\ mill} = M_{CO_2\ Diesel} + M_{CO_2\ Electricity\ \&\ steam} \qquad (2)$$

where ΔM represents the net emission of CO_2 from palm oil mill and M defines CO_2 release in individual process.

3-3. Bio-oil Production and Power Generation

Oil palm wastes from the mills, which are EFB and palm kernel shell, first undergo a pre-treatment process to remove the excess moisture. The fronds and trunks are not taken into account in this calculation. After initial drying of EFB, it undergoes shredding and pressing and then mixing with PKS and dried further in the open area about 2 to 3 days before being fed into the pyrolysis unit. The original moisture content of EFB is between 60 to 67% of its original weight [25]. In practice, the content of moisture in EFB can be reduced by shredding, pressing and drying in the open area for about 2 to 3 days. The entire moisture in the feedstock eventually goes to bio-oil. The high moisture content in feedstock thus results in bio-oil with high water content. The bio-oil with high water content is difficult to burn, on one hand, and the calorific value is lower, on the other hand. Therefore, it is a must to reduce the moisture content to around 10% in the feedstock before being fed into the pyrolyzer. However, to keep the cost down, it is proposed to dry the biomass under sun. Sometimes, if necessary, the waste heat from flue gas that is initially supplied to the pyrolyzer can be utilized for biomass drying.

After the pre-treatment process, the dry biomasses are fed into a pyrolyzer in the absence of air at 500-550 °C. The conceptual design of pyrolysis and power generation units is shown in Fig. 3. During the thermal decomposition of biomass, the vapor is condensed and collected as a main product, which is termed as bio-oil [26]. The by-product of this pyrolysis process is char and non-condensable gas, both of which can be combusted to provide heat to the pyrolyzer for consistent supply of pyrolysis heat [27] and the waste flue gas can be supplied through biomass supply line to completely dry it up. In our calculation it is found that the heat from the non-condensable gas combustion and charcoal combustion is quite more than required. This is because the fast pyrolysis that has been proposed in this study is exothermic and a little addition of external heat can keep the desired temperature for pyrolysis. It is assumed that the heat from only charcoal is enough to self-sustain the process. Therefore, after separation of liquid by condensation, the non-condensable gas can be cleaned and utilized as a fuel for one internal combustion engine to add power to the total generation.

Based on the energy required to produce 10 MW electricity, it is estimated that bio-oil to be needed is around 57.12 $t\cdot d^{-1}$. To produce this amount of bio-oil, around 87.84 $t\cdot d^{-1}$ of dry biomass is needed to be pyrolyzed. The pyrolysis plant is assumed to be integrated with the power plant to produce 10 MW power, which can be added to national grid [9]. The emission is calculated for this bio-oil production system based on emission factor of electricity, which is $6.89\times10^{-4}\ t\cdot CO_2\cdot(kWh)^{-1}$. The electricity generation efficiency of bio-oil is assumed to be the same as the natural gas power plants, which is 42% [9]. Using the combined heat and power (CHP) concept the overall efficiency can go up to 75%.

The biomass feedstock required was calculated by the power output and plant net thermal efficiencies. The power output of these systems is calculated based on the LHV of biomass and thermal efficiency of the power plant as shown in Table 5 [9,26,28,29]. Besides, the GHG emission from the total electricity generation and CO_2 emission from the direct combustion are calculated by using the emission factor in Table 6 [3].

Thus the total GHG emission at bio-oil production and power generation stages is determined by using these equations:

Table 5. Raw biomass properties

Parameter	Amount
Moisture, (wt%)	65.00
Fixed carbon, (wt%)	9.60
Organic volatiles, (wt%)	22.38
Ash content, (dry basis, wt%)	3.10
HHV, (daf, MJ·kg^{-1})	17.86
LHV, (daf, MJ·kg^{-1})	17.20

Table 6. Emission factor for grid electricity

Parameter	Value	Unit
CO_2 emission factor of grid electricity	0.59×10^{-3}	$t\cdot CO_2\cdot(kWh)^{-1}$
N_2O emission factor of grid electricity	3.00×10^{-9}	$t\cdot N_2O\cdot(kWh)^{-1}$
CH_4 emission factor of grid electricity	8.00×10^{-9}	$t\cdot CH_4\cdot(kWh)^{-1}$

Pyrolysis oil production:

$$\Delta M_{CO_2\ Pyrolysis\ Oil\ Production} = M_{CO_2\ Diesel} + M_{CO_2\ Electricity\ \&\ reactor} + M_{CO_2\ Heating} + M_{CO_2\ Pre\text{-}treatment} \quad (3)$$

Power generation:

$$\Delta M_{CO_2\ Power\ generation} = CO_2 \text{ emisson factor} \times \text{energy produce.} \quad (4)$$

where ΔM represents the net emission of pyrolysis and power generation and M defines CO_2 release in an individual process.

3-4. Transportation

In this LCA study, the emission from transportation is included since it contributes to a significantly large amount of GHG emissions. After performing backward calculation using CHP concept, it can be assumed that 5 mills are required to provide biomass feedstock by assuming that 1 small mill processes about 140 tons of FFB per day, thus generating a total of about 54 tons of dry EFB and 37 tons of dry PKS per day [15]. The emissions from transportation were calculated based on the distance of pyrolysis plant from palm oil mills as shown in Table 1 with an average distance of 80 km. It is also assumed that the distance between the plantation area to the mill and the pyrolysis plant to the power plant is negligible since the location is at the same site [30]. Power generation plant is assessed by presuming all the transportation is done by truck using petroleum derived-diesel (0.33 L·km^{-1}) [3]. Trucks with 20 tons of EFB loading are used to transport the biomass from oil palm mill to pyrolysis plant with a total round-trip distance of 160 km [13]. The emission factor from the transportation is shown in Table 7 [3].

The total GHG emission produced by transportation is calculated by using the equation below:

$$\Delta M_{CO_2\ Transportation} = CO_2 \text{ emission factor} \times \text{Distance} \quad (5)$$

where ΔM represents the net emission of CO_2 from transportation.

Table 7. Emission factor of greenhouse gas for transportation

Emission factor	Value	Unit
CO_2	1.10×10^{-3}	$t\cdot CO_2\cdot km^{-1}$
N_2O	3.10×10^{-8}	$t\cdot N_2O\cdot km^{-1}$
CH_4	$\times10^{-8}$	$t\cdot CH_4\cdot km^{-1}$

Table 8. Summary of the CO_2 assessment for 10 MW power generation using palm bio-oil

GHG ($t\cdot CO_2\cdot ha^{-1}\cdot y^{-1}$)	Absorption	Release
Palm oil cultivation and harvesting		9.65×10^{1}
Photosynthesis	1.61×10^{2}	
Respiration		
Fertilizer		1.16
Pesticides		1.22
Land use change		0.34
Palm oil mill		
Electricity & steam		3.45
Diesel		0.06
Pyrolysis oil production		
Diesel		0.06
Electricity & reactor heating		1.87×10^{1}
Pre-treatment		1.30
Power generation		
Electricity		5.6
Transportation		0.23
Total	1.61×10^{2}	1.28×10^{2}
Total GHG balance	3.2×10^{1}	

RESULTS AND DISCUSSION

1. Greenhouse Gas Assessment

The life cycle GHG emissions for the production and utilization of bio-oil are assessed as summarized in Table 8. The basis of the calculation is 10 MW electricity with 42% production efficiency from bio-oil. From backward calculation it is obtained that about 700 tons of FFB need to be processed to obtain the required amount, 154 t·d^{-1} of wet EFB and 46 tons of wet PKS, which is equivalent to 88 tons of dry and mixed feedstock, considering the moisture content of wet EFB, 65% and wet PKS, 21%. This amount of dry feedstock can produce 57 t·d^{-1} of bio-oil which is actually required to run a 10 MW power plant.

Based on Table 8, in the oil palm cultivation stage, it is assumed that oil palm plants act as carbon sink as they can absorb CO_2 about 1.61×10^{2} t·ha^{-1}·y^{-1} by photosynthesis and release CO_2 about 9.65×10^{1} t·ha^{-1}·y^{-1} by respiration of the tree [11]. It is assumed that the whole plantation areas considered in this study are drained peat land. Land use change in peat land contributes to the emissions of CO_2. Most of the peat carbon above drainage limit is assumed to be released to the atmosphere during all activities such as nursery establishment, site preparation, field establishment, field maintenance, harvesting, collection and replanting. The total amount of CO_2 emission from land use change is estimated to be about 0.34 t·ha^{-1}·y^{-1} [24]. Other than that, the usage of fertilizers and herbicides in the plantation area also releases CO_2 to the atmosphere with total of 1.16 t·ha^{-1}·y^{-1} and 1.22 t·ha^{-1}·y^{-1}, respectively [24].

At the FFB milling stage, the total CO_2 emission for the whole production of crude palm oil (CPO) and biomass feedstock is about 3.51 t·ha^{-1}y^{-1}. This emission is generally from the electricity consumption for the entire milling process and the diesel used for start-up of the boilers, which accounted in 3.45 t·ha^{-1}y^{-1} and 0.06 t·ha^{-1}y^{-1}, respectively.

At the bio-oil production stage, the major CO_2 emission comes from the biomass pre-treatment process, electricity consumption for pyrolysis process and emission from the steam boilers. During the EFB pre-treatment, the total energy consumption is 285.6 $MJ \cdot t^{-1}$ of EFB [3]. Based on the calculation, the total energy consumed during pre-treatment process is 15.87×10^6 $MJ \cdot y^{-1}$ and the total CO_2 released from pre-treatment process is 1.30 $t \cdot ha^{-1}y^{-1}$. During pyrolysis, a substantial amount of energy is required both in the form of electricity and heat. The amount of CO_2 emitted from the pyrolysis process is estimated to be about 1.87×10^1 $t \cdot ha^{-1}y^{-1}$ by assuming that the heat capacity of EFB is the same as wood due to insufficient data for EFB. In addition, the CO_2 emission from the diesel used for start-up the steam boiler in a pyrolysis plant is assumed to be the same as diesel used for start-up of the steam boiler in palm oil mill, which contributes around 0.06 $t \cdot ha^{-1}y^{-1}$.

In the utilization of bio-oil to produce 10 MW electricity stage, the GHG emission is estimated to be 5.60 $t \cdot ha^{-1}y^{-1}$ CO_2, 2.85×10^{-5} $t \cdot ha^{-1}y^{-1}$ N_2O and 7.60×10^{-5} $t \cdot ha^{-1}y^{-1}$ CH_4, respectively.

For the transportation sector, the average distance to transport biomass feedstock from palm oil mills to pyrolysis plant is 86 km and round trip distance is 172 km as shown in Table 1. Based on the calculation, the total amount of CO_2, N_2O and CH_4 emissions is 2.37×10^{-1} $t \cdot ha^{-1}y^{-1}$, 6.68×10^{-6} $t \cdot ha^{-1}y^{-1}$ and 1.29×10^{-5} $t \cdot ha^{-1}y^{-1}$, respectively.

From this study, based on Table 8, total CO_2 released and consumed starting from the beginning until the end of the whole production process is assessed. The total CO_2 emission for the whole production and utilization of bio-oil process is 1.28×10^2 $t \cdot ha^{-1}y^{-1}$ and the total CO_2 absorption by oil palm plantation is 1.61×10^2 $t \cdot ha^{-1}y^{-1}$. The net CO_2 emission can be determined by using the following equation:

$$\text{Net } CO_2 \text{ emission: } \Delta M_{CO_2\ \textit{Oil palm cultivation}} + \Delta M_{CO_2\ \textit{Palm oil mill}} + \Delta M_{CO_2\ \textit{Pyrolysis Oil Production}} + \Delta M_{CO_2\ \textit{Power generation}} + \Delta M_{CO_2\ \textit{Transportation}} \quad (6)$$

where ΔM represents the net emission of CO_2 from individual process.

Based on this calculation, the net CO_2 emission is –32.0 $t \cdot ha^{-1}y^{-1}$ (the negative value indicates more CO_2 is absorbed than released). The CO_2 emission for power generation using palm bio-oil can be considered as zero because the total CO_2 released can be fully absorbed by an oil palm plantation.

2. Impact of Utilization of Bio-oil as Power Generation

GHG emissions from the power generation using bio-oil from fast pyrolysis process are compared to the conventional fossil fuel-generated electricity. Fossil fuel based power plants (coal, natural gas or fuel oil) have higher emission as compared to bio-oil based power plant since it is a carbon neutral energy source. The major contributor to life cycle GHG emissions is the oil palm cultivation stage and pyrolysis stage.

Pyrolysis oil has a huge potential for power generation since it can overcome many problems associated with direct biomass combustion such as moisture absorption in the biomass storage. In addition, pyrolysis oil is more flexible for use in power plants as its co-firing with fossil fuels has been investigated and successfully tested on commercial scale. In large coal and natural gas power stations, bio-oil can be used as a co-firing fuel much more successfully compared to wood chips co-firing, and thus it can more easily displace solid fossil fuels (coal). Furthermore, the utilization of oil palm biomass via pyrolysis contributes more significantly in lowering the GHG emissions than that of the direct combustion of biomass. This is because the energy efficiency of direct combustion is less than half of the energy efficiency of the internal combustion of bio-oil.

In addition, the utilization of EFB as a feedstock for power generation via pyrolysis process is much more advantageous than that of the conventional mulching for fertilization of the plantation area. As reported, the nutrition value of 1 ton EFB is RM 14.40 when it is used as mulch, while it is RM 49.81 as a fuel for power generation [31,32]. In addition, the mulching is limited by labor and logistics and concerns about encouraging oil palm pests [31].

3. Risk Assessment

The risk of EFB usage as a main feedstock for pyrolysis process and power generation has been considered since EFB after being extracted at the mills contains high water of about 60-67%. It easily gets mold and rots under the exposure of rain and sun. Thus, pre-treatment and proper storage of EFB need to be done in order to avoid this situation. Other than that, regarding the crop yields, the palm oil fruit yield varies ±5% due to the unavoidable seasonal variation of FFB harvesting. At the pyrolysis stage, the moisture content in biomass is very sensitive. This is because the entire water ultimately goes into bio-oil and reduces the lower heating value of bio-oil as well as the burning properties. This ultimately affects the overall efficiency of power generation. Therefore, it is to be ensured that the moisture content in EFB feedstock for pyrolysis is as low as possible by pretreatment process. However, in the case of PKS, the initial moisture content is around 20-21%, which can easily be reduced during drying process to less than 10%.

In addition, bio-oil properties also depend on the pyrolysis conditions, especially temperature and heat transfer rate. If the pyrolysis temperature is comparatively low with low heat transfer rate to the biomass particle, then slow pyrolysis is assumed to be occurring, which facilitates the formation of water by re-polymerization of small organic molecules in the vapor phase. This can be prevented by keeping the pyrolysis temperature above 500 °C and providing solid to solid heat transfer media in the pyrolysis reactor, which can ensure the fast pyrolysis of the feedstock. Fast pyrolysis can provide a large fraction of smaller organic molecules in the bio-oil, which undergoes clean combustion into the internal combustion engine. Slow pyrolysis provides a large fraction of heavier organic molecules, which are viscous and difficult to atomize. Therefore, the combustion of them in the engine is not often completed.

CONCLUSION

Bio-oil can be produced through fast pyrolysis process from solid biomass and then combusted to generate power, replacing fossil fuels as feedstock. In this study, solid biomass from palm oil mills is proposed to be used as feedstock for the production of bio-oil. The combustion of bio-oil for power generation is expected to reduce GHG emission more than the combustion of fossil fuel. Pyrolysis oil has the potential to replace fossil fuels as an alternative energy source to generate power, reducing GHG emissions. In terms of GHG assessment, the production of palm bio-oil via fast pyrolysis to generate 10 MW power brings no negative impact to the environment as the amount of CO_2 emitted to the atmosphere is much lower than that of the CO_2 absorbed from the atmosphere during cultivation of oil palm. The results of this LCA study show that palm bio-oil has the potential to become the major renewable energy source in the future since the GHG emission is negative throughout the whole process.

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