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Energy balances, greenhouse gas emissions and economics of biochar production from palm oil empty fruit bunches

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ABSTRACT

This paper presents results from a gate-to-gate analysis of the energy balance, greenhouse gas (GHG) emissions and economic efficiency of biochar production from palm oil empty fruit bunches (EFB). The analysis is based on data obtained from EFB combustion in a slow pyrolysis plant in Selangor, Malaysia. The outputs of the slow pyrolysis plant are biochar, syngas, bio-oil and water vapor. The net energy yield of the biochar produced in the Selangor plant is 11.47 MJ kg^{-1} EFB. The energy content of the biochar produced is higher than the energy required for producing the biochar, i.e. the energy balance of biochar production is positive. The combustion of EFB using diesel fuel has the largest energy demand of 2.31 MJ kg^{-1} EFB in the pyrolysis process. Comparatively smaller amounts of energy are required as electricity (0.39 MJ kg^{-1} EFB) and for transportation of biochar to the warehouse and the field (0.13 MJ kg^{-1} EFB). The net greenhouse gas emissions of the studied biochar production account for 0.046 kg CO_2-equiv. kg^{-1} EFB yr^{-1} without considering fertilizer substitution effects and carbon accumulation from biochar in the soil. The studied biochar production is profitable where biochar can be sold for at least 533 US-\$ t^{-1}. Potential measures for improvement are discussed, including higher productivity of biochar production, reduced energy consumption and efficient use of the byproducts from the slow pyrolysis.

1. Introduction

1.1. Background

Global warming has received much attention in recent years. The rising concentration of carbon dioxide (CO_2) in the atmosphere from 370 to 392 ppm from 2000 to 2011 is seen as one of the major drivers for global warming (NOAA/ESRL, Mauna Loa Record, 2012). Measures for sequestrating CO_2 from the atmosphere are being discussed to prevent the continuation of global warming in coming years (Read, 2009). Increasing soil organic carbon through carbon application of biochar to soils has been proposed as one measure among others for sequestrating CO_2 from the atmosphere (Lehmann et al., 2006; Pratt and Moran, 2010). Biochar is a carbon-rich substance obtained when biomass, such as wood, manure or leaves, is heated in a closed container without any oxygen (Gaunt and Lehmann, 2008). Currently, there are various processes to produce biochar, including, among others, slow pyrolysis, fast pyrolysis and hydrothermal conversion (Sevilla and Fuertes, 2009).

In recent years, researchers such as Marris (2006), Lehmann (2007) and Woolf et al. (2010) investigated the impact of biochar application on agricultural land as a measure for improving soil fertility, reducing GHG emissions and fixing carbon in the soil. Generally, when the CO_2 is taken by the plants from the atmosphere as they develop, then, automatically, the CO_2 is emitted through the decomposition process after the plant died. This natural cycle is considered as carbon neutral (Brownsort, 2009). Considering that CO_2 is captured from the atmosphere to produce the biochar, the net process might be carbon negative (Pratt and Moran, 2010). Biochar has a high content of stable carbon, typically between 50%

Abbreviations: BEP, break-even-point; BET, surface area according to Brunauer, Emmet and Teller (BET); C, carbon; CEC, cation exchange capacity; CPO, crude palm oil; EFB, empty fruit bunches; FFB, fresh fruit bunches; GHG, greenhouse gases; GWP, global warming potential; h, hour; ha, hectare; IRR, internal rate of return; km, kilometer; L, liter; MPOB, Malaysia Palm Oil Board; NPV, net present value; N_2O, nitrous oxide; ppm, parts per million; RoI, return on investment; t, ton; UNEJ, University of Jember – Indonesia; UPM, Universiti Putra Malaysia.

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and 85% (Downie et al., 2009), which resists decay and remains in soils for long periods of time, compared to the mean residence times of decades to centuries for most other soil organic matter pools (Blackwell et al., 2010).

Besides these climate-change related aspects, Yanai et al. (2007), Cowie (2008) and Rondon et al. (2009) found increasing evidence suggesting that the application of charcoal to soils with very low fertility could increase yields of agricultural crops and improve several soil quality indicators by improving the nutrient availability and soil water-holding capacity, avoiding and reversing the soil degradation associated with long term cultivation, improving the soil biological health through proliferation of beneficial microorganisms (Lehmann, 2007; Laird, 2008). Biochar production has also been promoted as an environmentally friendly technology to dispose some organic wastes and produce feedstock for renewable energy (Chan et al., 2007).

1.2. *Pyrolysis for biochar production*

Pyrolysis is a thermo-chemical decomposition process in which organic material is converted into a carbon-rich solid as well as volatile matter by heating in the absence of oxygen (Demirbas, 2001). The two main types of biomass pyrolysis processes are the fast pyrolysis and the slow pyrolysis.

The fast pyrolysis was widespread used to produce liquid fuel from wood during the oil crisis in the last century. The process is designed to give a high yield of bio-oil (Bridgwater and Peacocke, 2000; Bridgwater et al., 2002). Demirbas (2001) distinguishes the fast pyrolysis by the heating value and short vapor residence times. A specific requirement of the fast pyrolysis is the small size of the feedstock particles and the type of feedstock, which allows removing the vapor as quick as possible from the hot solid. This type of pyrolysis takes place at a temperature of around 500 °C.

The slow pyrolysis is characterized by a lower heating value, relatively long solid and vapor residence times and a process temperature of around 400 °C (Bridgwater, 2007). The main goal of the slow pyrolysis is to produce char. Technologies applied for slow pyrolysis are generally based on a horizontal tubular kiln where the biomass is moved at a controlled rate through the kiln; these include agitated drum kilns, rotary kilns and screw pyrolyzers.

A comprehensive review of modern slow pyrolysis techniques is still missing. However, Brown (2009) summarizes them briefly together with other potential techniques for biochar production. Several researchers have examined the pyrolysis process in terms of its economic (Bridgwater et al., 2002; Wright et al., 2010) and environmental performances (Laird, 2008; Roberts et al., 2010). Their studies have shown that there is a wide range of biomass applications including heat and power generation, fuel production, soil amendment and carbon mitigation strategies. Ringer et al. (2006) stated that the non-condensable gases and biochar are used to provide heat and energy. This is supported by Mullaney et al. (2002) who found that the pyrolysis products could create energy to heat the pyrolysis and other applications. Several process designs have considered the heat and power generation from the pyrolysis products, as developed by Bridgwater et al. (2002).

1.3. *Biochar feedstock*

Empty fruit bunches (EFB) of palm oil are one of the major solid wastes from the palm oil production industry besides fibers and shells. The EFB of palm oil are highly abundant in palm oil producing countries, such as Indonesia and Malaysia (Yee et al., 2009; Abubakar et al., 2010), yielding nearly 1.5 million t yr^{-1} for both countries.

EFB is a source of biomass that can be readily converted into energy.

Table 1
Characteristics of the biochar production facility in Selangor, Malaysia.

Parameter	Description
Palm oil EFB transportation	Truck size: 7 t
Distance from palm oil mill to biochar plant	<1 km
Distance from biochar plant to plantation	19 km
Distance from palm oil mill to plantation	17 km
Project lifetime	20 years
Working hours per day	22 h
Electricity consumption	1.08 kWh d^{-1}
Operating days per year	240 days
Quantity of feedstock processed per day	20 t EFB
Quantity of feedstock processed per year	4800 t EFB
Quantity of biochar produced per year.	960 t biochar
Type of kiln	Box oven-hot gas recirculation
Temperature	350–450 °C
Residence time	4 h
Thermal energy requirement	Recycle gas
Size of facility	1000 m^2

The incineration of EFB at the mills has contributed to air pollution (Abubakar et al., 2010). Therefore, the Malaysian government has introduced regulations, which prompt mills to look for alternative management methods for the disposal of the EFB.

Alternatively, the EFB are used as mulch (Abubakar et al., 2010). In addition to reducing air pollution, the application of EFB to the field helps to control weeds, prevent erosion and maintain soil moisture in the surrounding palm oil trees (Lim and Zaharah, 2000). However, due to high GHG emissions from mulch of EFB, rising costs of labor, transportation and dispersion needed to apply EFB, less costly ways for valorizing the EFB are being explored. Abubakar et al. (2010) emphasize that the transport of the EFB from the mills to the fields is a major cost factor for plantation companies. One option to save expenditures would be to have a biochar production site near the mill. This would reduce transportation costs for EFB by truck or lorry and potentially generate added value from using biochar as soil amendment. Nevertheless, the processing of EFB to make biochar is costly and economic efficiency remains to be evaluated.

Until today, very little is known about the production of biochar from palm oil EFB. This study aims to assess the energy demand, GHG emissions, as well as the costs and economic efficiency of biochar production from palm oil EFB via slow pyrolysis.

2. Methodology

2.1. *Case study and data collection*

This analysis is based on information from a biochar plant designed to process palm oil EFB for biochar in Selangor, Malaysia. The plant is funded by the Ministry of Science, Technology and Innovation (MOSTI) of the Government of Malaysia, in cooperation with the Department of Chemical and Environmental Engineering of the Faculty of Engineering at the Universiti Putra Malaysia (UPM) in Malaysia. The plant started to operate in January 2010. Since then, it has been operated by the private company Namstech Sdn Bhd, Selangor, Malaysia.

For the analysis, we use technical and economic data on plant operations, from January 2010 until July 2011. The data for this analysis was collected using interviews with plant operators and managers from the company as well as scientists from UPM between January 2011 and July 2011. The characteristics of the biochar production facility in Selangor, Malaysia, are shown in Table 1.

2.2. *Data analysis, tools and system boundaries*

In this investigation, *Life Cycle Assessment* (LCA) methodology is implemented to study the production of biochar from EFB in terms

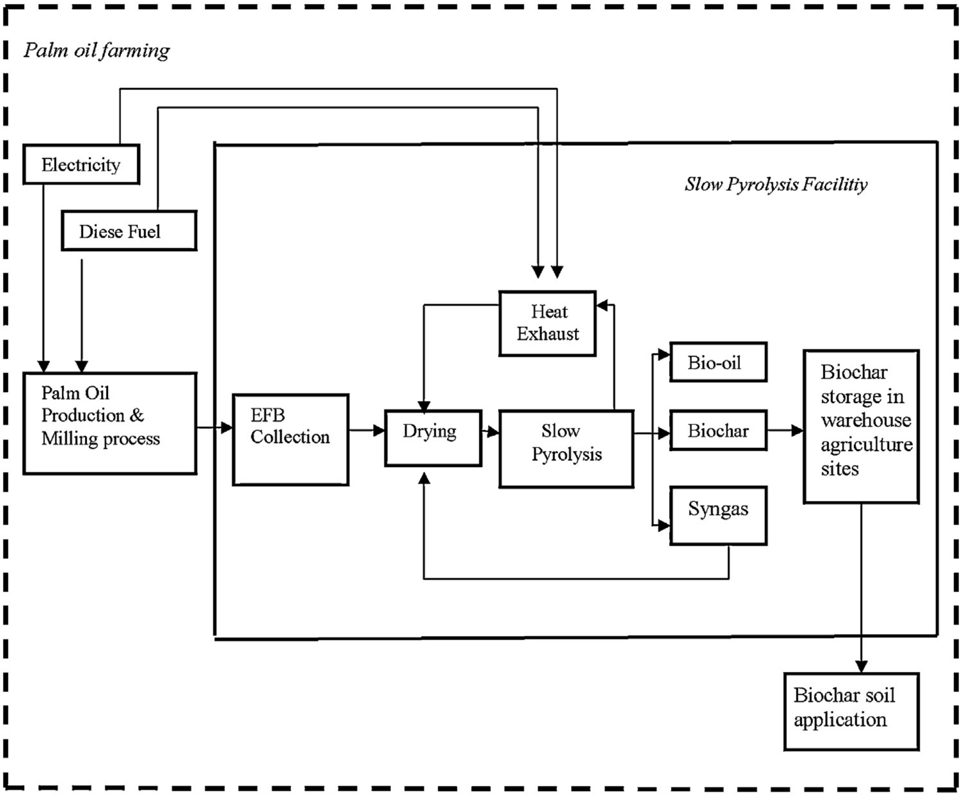

Fig. 1. System boundaries of biochar production are denoted by the inner box.

of energy efficiencies and GHG emissions. The energy and GHG balances were calculated using the LCA software Umberto® (ifu/ifeu, 2005).

The balances encompass in a gate-to-gate analysis the pre-chain processes (e.g. diesel fuel and electricity) and the slow pyrolysis process for biochar production. The "gate-to-gate" analysis includes a systematic inventory and examination of the environmental impact caused by the product starting from its production, transportation, processing and extraction of raw material, and distribution, but not including the application of the product in the field. The analysis includes the material and energy inputs and outputs of each process stage. The emissions are calculated based on the material and energy inputs on a per year basis. The total material and energy inputs are related to the biochar output of the plant, i.e. the functional unit is 1 kg of biochar from EFB. Fig. 1 shows the system boundaries of the gate-to-gate analysis in this study.

The energy balances, GHG emissions and economics of biochar production from EFB are analyzed and compared with the reference system, i.e. the direct application of EFB to the trees in the palm oil plantation. The energy content as well as the GHG emission factors are shown in Table 2.

EFB is a source of organic matter and plant nutrients, including 2% Potassium (K), 0.54% Nitrogen (N), 0.19% Magnesium (Mg) and 0.16% Phosphorous (P) (Abubakar et al., 2010). The amount of mineral fertilizer can possibly be reduced by applying EFB and biochar from EFB to the soil. However, the fertilizer substitution potential of biochar from palm oil EFB is still a matter of research. Therefore, we do not include the effect of fertilizer savings in this gate-to-gate analysis.

The energy demand, the GHG emissions and the costs of the agricultural production processes are allocated according to the economic value generated from selling the products from palm oil production (i.e. economic allocation). These products are: crude palm oil (CPO), kernel oil and EFB.

Based on their economic value, the allocated shares of the products are 67.0% for CPO, 31.7% for kernel oil and 1.3% for EFB, as shown in Fig. 2. Accordingly, 1.3% from the total energy demand and GHG emissions from palm oil production are allocated to the production of EFB.

2.3. Description of the biochar production process

The biochar production process starts with the palm oil plantation or agricultural production, comprising land preparation, raising and planting of seedlings, application of fertilizers, herbicides and pesticides, harvesting, transport and milling of fruits. The analysis of the agricultural production process is based on the results of previous studies from Yusoff and Hansen (2007), Yee et al. (2009) and Harsono et al. (2012).

EFB are obtained after extraction of the fruits from the fresh fruit bunches (FFB) during the milling process for palm oil production.

Table 2
Energy content and GHG emission factors of materials and energy sources.

Factor	Energy content	GHG emission
Diesel fuel	41.33 MJ kg^{-1} (Fritsche and Schmidt, 2001)	87.5 g CO_2-equiv. kg^{-1} (Fritsche and Schmidt, 2001)
Electricity	–	134.2 g CO_2 MJ^{-1} (Hallmann, 2000)
Biochar	28.61 MJ kg^{-1} (Khor and Lim, 2008)	
Syngas	9.8 MJ kg^{-1} (Omar et al., 2010)	
Bio-oil	36.30 MJ kg^{-1} (Imam and Capareda, 2011)	

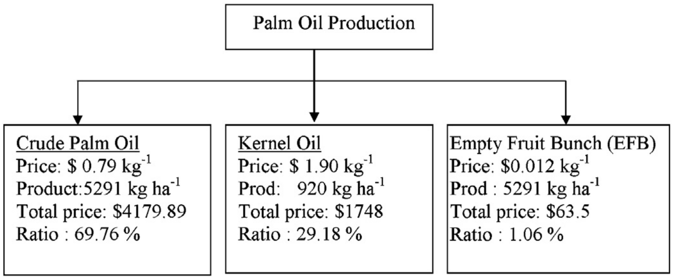

Fig. 2. Quantities, prices, values and allocation ratio for products from palm oil production used for allocation of energy inputs and GHG emissions based on economic values.

Source: Personal Communication, MPOB (2011).

At this stage, EFB have a moisture content of 12%. They are stored for drying by natural convection in an open place. When the EFB reach a moisture content of about 9%, they are moved from the mill to the biochar plant using trucks with a loading capacity of 7 t. The biochar plant is located at a distance of about 1 km from the palm oil mill. The transportation of the EFB from the mill to the biochar plant requires energy and produces emissions.

The biochar plant is fed using screw belts to move the EFB from the trucks to the pyrolysis drums, where they are processed for further drying. The EFB are fed to the pyrolysis drums without shredding. The pyrolysis equipment comprises three ovens and three rotating drums. The drying and pyrolysis process is designed in such a way that when the drying of one batch is completed, the processing of the next batch gets started in the next drum. To start the process, the oven is heated with hot air generated in a burner using diesel fuel. The temperature used for the slow pyrolysis is between 350 °C and 450 °C. The slow pyrolysis process requires extensive use of diesel fuel for heat generation. During operation in 1st and 2nd hours, no further diesel is required, as the heat production is supported by the syngas obtained as a byproduct from the pyrolysis process. The syngas produced during slow pyrolysis is utilized to generate additional heat for drying and slow pyrolysis. Excess energy is dissipated through a chimney. The daily production for one batch is 20 t of EFB, including drying and pyrolysis.

Furthermore, electricity is used for operating computer panels, lamps and other equipment with a total consumption of 1.08 kWh d^{-1}. The byproduct bio-oil is not used, but disposed as a waste. After production, the biochar is transported to a storage facility located at a distance of 19 km using trucks with a loading volume of 7 m^3, equivalent to a load of 7 t of biochar with a density of 1.10 kg m^{-3}. The biochar plant in Malaysia is shown in Fig. 3.

In the analysis, we did not include the process of applying the EFB or biochar to the palm oil trees in the plantation, because there is no information available at the moment about the GHG emissions from the application of EFB and biochar to palm oil trees.

2.4. Database

The data used for the GHG emissions and energy balances are taken by interview with plant operators and also taken from references of Yusoff and Hansen (2005), Yee et al. (2009) and Harsono et al. (2012). The respective information is compiled in Table 3, including data on agrochemical inputs such as fertilizer and pesticides, energy for transportation and the industrial phase.

According to Yee et al. (2009), 1 ha palm oil trees yields in Malaysia between 20 and 22 t of FFB. The share of EFB from the total harvested biomass is 23%, i.e. 1 ha of palm oil plantation produces 4.6 t of EFB. Accordingly, the EFB processed daily by the biochar plant is equivalent to the EFB harvested from around 4.35 ha.

The EFB production process includes the steps of production, harvest, and collection, all of which involve costs. This implies costs for the inputs, resources and activities required to raise, harvest, collect and deliver the EFB to the mill, including seeds, fertilizers, diesel fuel, equipment, labor and land. The pyrolysis process requires energy supplied by diesel fuel and electricity from the grid to operate the machines and equipment. The burner is fueled with 60 L h^{-1} diesel oil to generate the heat needed for combustion during the starting phase of the process. Once the process is running, the diesel oil consumption is reduced to 40 L h^{-1}, and some diesel is substituted by the byproduct syngas for heat generation.

2.5. Production economics analysis

In the production-economics-analysis, we assess the total costs, outputs, revenues and profits related to biochar production in the studied facility in Selangor, Malaysia. The analysis takes into account the operational costs, fixed costs and revenues from biochar production and sales (Granatstein et al., 2009). The cost analysis includes all expenditures for inputs and other charges that were incurred during the operation of the biochar production facility in Selangor during the period of one year. The fixed costs

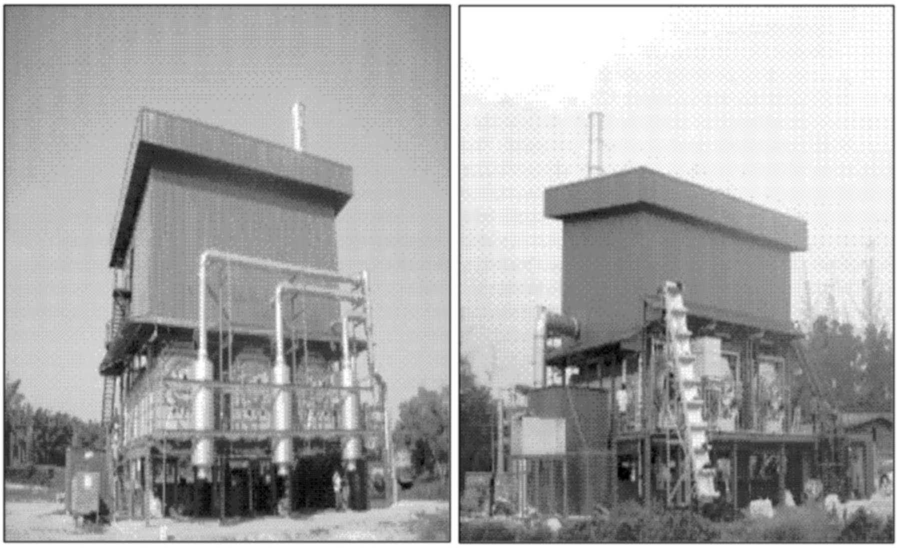

Fig. 3. Biochar plant in Selangor, Malaysia.

Table 3
Prices of selected inputs.

Selected inputs	Unit	Price (US$)	Source
Palm oil EFB	t	15.8	MPOB (2011) (personal communication)
Rent of land	$1000\,m^2\,yr^{-1}$	3800	UPM biochar business management (2011) (personal communication)
Labor	Day/person	15.9	UPM biochar business management (2011) (personal communication)
Diesel fuel price	L	0.63	UPM biochar business management (2011) (personal communication)
Electricity	kWh	0.12	UPM biochar business management (2011) (personal communication)

include expenditures for items that do not vary depending on the production level, e.g. the rent for the land where the facility is installed. All other costs that change according to the change in the volume of production are subsumed under the items variable or operation costs. The variable costs include EFB feedstock costs, labor costs, costs for fuel and electricity, transportation costs and costs for repair and maintenance of equipment, machines and buildings. To calculate the depreciation of buildings, equipment and machines, we used a straight-line method. This method assumes that the annual depreciation of tools and machines is constant. Investments considered in the analysis include the capital for the construction of the project plus interest payments during development.

The *net present value* (NPV) is used to assess the difference between the present value of the investment with the present value of net cash receipts (operations and residual value) in the future. The purpose of using the NPV in this study is to assess investment opportunities in the procurement of equipment and processing of biochar from palm oil EFB. The equation used to calculate the NPV is as follows (Boardman et al., 1996):$NPV = \sum_{r=1}^{n} \frac{C_i}{(1+r)^i}$ where C_i are the expected (i.e. average) values of the cash flows in each period (in US$), r is the risk-adjusted discount rate (in %) and i is the interest rate (in %).

An investment can be economically profitable if the NPV is positive. The bank interest rate used of 6.6% (The Central Bank of Malaysia, 2011) is fixed during the project's lifetime over a period of 20 yr^{-1}. In the studied case, revenues result from sales of the biochar to the palm oil plantation as soil amendment at a price of 15.8 US$ t^{-1}.

The break-even-point (BEP) is used in this study to determine the amount of biochar that the company needs to produce in order to avoid losses and gain profits. For determining the BEP, we use the following formula (Boardman et al., 1996):$BEP = \frac{TFC}{P-c}$ where the BEP is the total biochar production (in t yr^{-1}), TFC is the total fixed costs (in US$ yr^{-1}), P is the product price (in US$ t^{-1}) and c is the variable costs (in US$ t^{-1}).

The *benefit–cost-ratio* (B/C-ratio) compares the benefits with the costs of the project investment. The analysis of the B/C-ratio is used in this study to determine the economic feasibility of the biochar production facility during its life. The B/C-ratio is calculated using the following formula (Boardman et al., 1996):B/C-ratio = $\frac{\sum_{i=1}^{n} B/(1+r)^i}{\sum_{i=1}^{n} C/(1+r)^i}$ where B/C-ratio is the *benefit–cost-ratio*, B is the benefit (in US$ yr^{-1}), C is the costs (in US$ yr^{-1}), i is the interest rate (in %) and r is the risk-adjusted discount rate (in %).

According to Boardman et al. (1996) the economic feasibility of an investment or project is given if the B/C-ratio > 1 and the NPV is greater than zero. This means, the project in question may be implemented economically when the benefits to be obtained during the technical–economical life of the project are greater than the costs plus the investment.

The internal rate of return (IRR) can be thought of as the net rate of return on investment. This result for the IRR can compare with the interest rate applicable and can facilitate in the selection of a "discount rate" accordingly. The IRR is calculated using the following formula (Boardman et al., 1996):$IRR = i' + \frac{NPV'}{NPV''-NPV'}(i''' - i')$where IRR is the internal rate of return (in %), i' is the discount rate (in %), NPV' is the net present value at discount rate i' (in US$) and NPV'' is the net present value at discount rate i'' (in US$).

The *payback period* (Pb) is the period of time required to return the investment. The analysis of the Pb in this study aims to determine the length of time required for the return on capital investment in the biochar production facility. The formula used is as follows (Boardman et al., 1996):$Pb = \frac{I}{(TR-TC)+D}$ where Pb is the *payback period* (in yr), I is the investment (in US$), TR is the total revenue (in US$ yr^{-1}), TC is the total cost (in US$ yr^{-1}) and D is the depreciation (in US$ yr^{-1}).

The return on investment (RoI) indicates the net revenues (i.e. total revenues minus total costs) of a project divided by the total costs. This ratio is used to highlight the magnitude of potential returns versus costs. A sensitivity analysis was carried out to assess the economic vulnerability of the biochar production toward possible changes occurring during the lifetime of the investment. The sensitivity analysis comprises changes of the parameters feedstock costs, EFB and biochar sales price and diesel fuel price. The sensitivity analysis is indispensable for making decisions on investments, especially in critical situations such as rising raw material prices, rising fuel prices and declining sales prices of products.

3. Results and discussion

3.1. Biochar production

The products obtained from the slow pyrolysis of palm oil EFB in the biochar facility are biochar, syngas and bio-oil. The biochar production efficiency is 20%, i.e. 1 t of EFB delivers 0.2 t of biochar. In addition, 0.3 t of syngas and 0.025 t of bio-oil are obtained as byproducts from each ton of EFB. The biochar produced is composed of carbon (C), nitrogen (N), ash and water. Biochar also produce volatile matter which is material with evaporates readily at normal temperature, pressure and vaporized with value of 41% as shown in Table 4.

Table 4
Properties of biochar from palm oil EFB.

Properties	Unit	Value
Water content	%	6
Ash	%	7.68
C content	%	45
N content	%	0.32
Volatile matter[a]	%	41
P	g/g	426
K	g/g	14.20
Ca	g/g	379
Mg	g/g	290
BET surface[b]	m^2/g	2.71
Cation exchange capacity	$Cmol^{(+)}/kg$	42.85

[a] Volatile matter is material that evaporates readily at normal temperatures and pressure which can be readily vaporized. pressures and can be readily vaporized.

[b] BET surface: Brunauer, Emmet and Teller (BET) surface area (Keiluweit et al., 2010).

Table 5
Comparison between biochar properties from several feedstocks.

Property	Late stover	Switch grass	Rice husk	Palm oil EFB (in this study)
Moisture content (% in DM)	15[a]	12[b]	12[c]	6[d]
Ash content (% in DM)	5.6[a]	5.6[b]	4.5[c]	7.7[d]
C content of feedstock (% in DM)	45[a]	45[b]	44[c]	45[d]

Remark: DM, dry matter.

[a] Scurlock (2009).

[b] Boateng et al. (2007).

[c] Masulili et al. (2010).

[d] Own data from biochar plant in Selangor.

Biochar yields produced from palm oil EFB in Selangor were 20% of the feedstock mass, while biochar yields of 35–36.5% of the feedstock mass are reported by Downie et al. (2009) for other kinds of feedstock. A reason for this may be the different physical and chemical properties of palm oil EFB compared to other feedstock. The properties of biochar from several feedstocks are shown in Table 5.

The water content of biochar from palm oil EFB is the smallest compared with biochar from other feedstock. It is only half of the water content of biochar from rice husk and switchgrass. Compared with other feedstocks, the biochar from palm oil EFB is relatively fine and the ash content high. This may be an advantage for transportation, application and incorporation of the biochar into the soil. This is might be because of higher density of biochar. Table 5 indicates that the carbon content of all feedstock is similar.

3.2. Energy balance

The total energy demand of the biochar production process is 2.75 MJ kg^{-1} EFB as seen in Table 6. The largest energy input is for the diesel fuel consumed during the pyrolysis (i.e.: 2.31 MJ kg^{-1} EFB), followed by electricity consumption (0.39 MJ kg^{-1} EFB), transportation of biochar to the warehouse (0.15 MJ kg^{-1} EFB) and transportation of biochar to the field (0.002 MJ kg^{-1} EFB). The energy input from syngas used for heat generation is 63.71 MJ kg^{-1} EFB. The syngas used to generate heat is an output from the pyrolysis of palm oil EFB. The energy supplied from diesel fuel is the largest energy input totaling 84% of the total energy input. The syngas produced in the slow pyrolysis supplies up to 33% of the energy required in the process.

Brownsort (2009) stated that the liquid as well as the gas which are produced during the burning of biomass can be used for electricity generation. In the biochar plant in Selangor, the liquid bio-oil from the slow pyrolysis is currently disposed as waste. The syngas from the process is used to produce heat for the pyrolysis process. The total energy output in the form of syngas is 7.59 MJ kg^{-1} EFB. The total energy output in the form of biochar from the slow pyrolysis is 5.72 MJ kg^{-1} EFB. The energy output in the form of bio-oil is 0.91 MJ kg^{-1} EFB. The total energy content of the products from the slow pyrolysis is 14.22 MJ kg^{-1} EFB. The net energy yield is 11.47 MJ kg^{-1} EFB and the ratio energy output/input is 2.8. The energy output/input ratio found is less than the ratio of 6.9 reported for corn stover and 5.3 for switchgrass (Gaunt and Lehmann, 2008). Roberts et al. (2009) found ratios of 2.8 for stover and 3.1 for switchgrass. The energy flows from feedstock to product is shown in Fig. 4.

Table 6
Energy input and output for biochar production.

	Input	Energy input (MJ kg^{-1} EFB)
1.	Farming and mill processing[a]	0.03
2.	Transport EFB to biochar plant	0.006
3.	Energy from diesel fuel used for pyrolysis	2.31
4.	Electricity generation	0.39
5.	Transport of biochar to warehouse	0.02
6.	Transport of biochar to the plantation	0.002
	Total	2.76
	Output	**Energy output (MJ kg^{-1} EFB)**
1.	Biochar	5.71
2.	Syngas	7.59
3.	Bio-oil	0.91
	Net energy yield (syngas only)	7.59
	Ratio output/input	2.75

[a] Allocation of 1.3% from total energy input to palm oil production, including agricultural farming, transportation and milling.

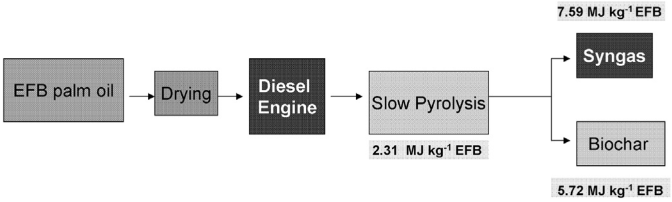

Fig. 4. Energy flows from feedstock to product.

The energy input of the reference system is 10.65 MJ kg^{-1} EFB, and mainly consists of the energy input for transportation of the fresh EFB to the palm oil plantation. This is 13.04 MJ kg^{-1} EFB less energy compared to the energy input for the production of biochar and transportation to the palm oil plantation. These data is shown in Table 6.

3.3. Greenhouse gas emissions

Table 7 shows that the total GHG emissions of the biochar production facility in Selangor (Malaysia) using palm oil EFB are 0.046 kg CO$_2$-equiv. kg^{-1} EFB yr^{-1}.

GHG emissions are the highest during the process step of biochar production (61.3%), followed by EFB production (23.2%), electricity generation from the grid (13.9%), transport of biochar to the warehouse (0.5%), transport of biochar to the fields (0.9%), and transport of EFB to the biochar plant (0.1%). The highest share of GHG emissions in biochar production is caused by the diesel fuel consumption in the slow pyrolysis process. The GHG emissions in the reference system resulting from the direct transportation and application of EFB are 0.039 kg CO$_2$-equiv. kg^{-1} EFB yr^{-1}. This is 0.18 kg CO$_2$-equiv. kg^{-1} EFB yr^{-1} less compared to the GHG emissions from the production and transport of biochar from palm oil EFB.

Table 7
Global warming potential emissions of biochar from palm oil EFB.

	GHG emission	(g CO$_2$-equiv. kg^{-1} EFB yr^{-1})
1.	Farming and mills processing	1.49
2.	Transport of EFB to biochar plant	0.10
3.	Slow pyrolysis	35.94
4.	Electricity generation	8.22
5.	Transport of biochar to warehouse	0.29
6.	Transport of biochar to the plantation	0.01
	Total	46.05

Table 8
Results of production economics analyses.

No.	Parameter	Unit	Value
1.	Investment	US$	1265.823
2.	Remaining value	US$	126.582
3	Total fixed cost	US$ yr^{-1}	170.226
4	Total variable cost	US$ yr^{-1}	353.408
5	Total cost	US$ yr^{-1}	523.634
6.	Total revenue	US$ yr^{-1}	531.646
7.	Net present value (NPV)	US$	129.621
8.	Benefit/cost-ratio (B/C-ratio)	–	1.02
9.	Payback period (PB)	yr	9.97
10.	Break-even-point (BEP)	t of biochar	901
11.	Internal rate of return (IRR)	%	8.96
12.	Return on investment (RoI)	%	17.58

When the biochar is applied to the soil, it is crucial to quantify the possible GHG emissions (CO_2, N_2O and CH_4), because any positive carbon sequestration effect could be diminished, or even reversed. Reduction of N_2O when biochar was applied in the soil as stated by Rondon et al. (2005) as supported by Clough et al. (2010) who stated that the carbon dioxide (CO_2) and nitrous oxide (N_2O) are the main GHG emissions which will be affected when biochar is applied to the soil. He showed that a near complete suppression of methane upon biochar addition at an application to soil. Since then, many reports have been published regarding the reduction of N_2O emissions by application of biochar to soil (Zwieten et al., 2009 and Clough et al., 2010).

Land use change can result in a decrease of the organic carbon stored in the soil. Although land conversion only happens once, its effect can be large and long-lasting. The soil reaches a new (lower) carbon content at a decaying-exponential rate, characterized by an about 20-year time-constant and an annual CO_2 emission of the order of 3.7 t ha^{-1} (Commission of the European Communities, 2009) with the uncertainty range being more than 50%. Land use change is to be the most decisive factor in overall GHG emissions (Wicke et al., 2008). Palm oil energy chains based on land that was previously natural rainforest or peat land have such large emissions, that they cannot meet GHG emission reduction targets of 50–70% as demanded by the Cramer Commission in the Netherlands (Cramer, 2006).

3.4. Economic assessment

The yearly costs in the reference system, i.e. the direct transportation and application of unprocessed EFB to the palm oil plantation, are 26,459 US$ yr^{-1}. The costs for transportation of biochar to the palm oil plantation are 5075 US$ yr^{-1}. The costs for the transportation of biochar to the palm oil plantation is only about 25% of the total costs for the transportation of EFB to the palm oil plantation in the reference system. Therefore, the project will save transportation costs of 21,384 US$ yr^{-1}. The total costs of biochar production at the plant in Selangor are 523.634 US$ yr^{-1}. The total revenue from sales of biochar are 531.646 US$ yr^{-1}. The benefit of the production of biochar is 8012 US$ yr^{-1}. These data is shown in Table 8.

The *net present value* (NPV) of the biochar production investment in Selangor, Malaysia, is greater than zero, which indicates that the investment project for biochar production is economically feasible. The NPV is determined by the amount of investment and the net revenue in the business. The *benefit–cost-ratio* (B/C-ratio) of 1.02 is positive, indicating that the investment in the production of biochar production is economically profitable. The *payback period* (Pb) of the investment is 9.97 yr^{-1}. The *internal rate of return* (IRR) of the biochar production project is 8.96%. Since the IRR is higher than the bank interest, the project may be assessed as economically viable.

The profit margin of biochar production from palm oil EFB in the plant in Selangor is 11.59 US$ t^{-1} of biochar produced. The calculated yearly return on investment (RoI) for the biochar production is 17.58% and the break-even-point (BEP) is reached at a total yearly output of 901 t biochar.

The sensitivity analysis suggests that the economic viability of the project is very susceptible to the costs for the EFB feedstock, the price for diesel fuel and the price of biochar, which are the major determinants of the production costs and revenues. Financial parameters develop negatively when the price of biochar decreases slightly. An increase in the diesel fuel price of more than 5% may yield a negative result, if the other techno-economic parameters remain constant. The price for palm oil EFB is allowed to increase not more than 15% (i.e. 18.20 US$ t^{-1}) without putting the economic factors of the project at risk, when all other parameters remain constant.

4. Conclusion

This study presents energy balances, greenhouse gas emissions and production economics of a biochar production facility using palm oil EFB in Selangor, Malaysia. Biochar production is practiced here as a strategy to overcome the shortcomings of direct application of EFB to the palm oil plantation. The share of the products obtained from the slow pyrolysis at the biochar production facility are in percent of the total feedstock 20% biochar, 30% syngas, and 2.5% bio-oil. The energy input needed for the process mainly stems from diesel fuel and syngas produced during the slow pyrolysis of the palm oil EFB. The process is characterized by a high requirement of energy (i.e. diesel fuel and electricity) for generating heat for combustion and operating the facility. However, the energy output/input ratio of the biochar production is positive; the energy input for biochar production and transportation to the field is more than two times higher than the energy consumed in the case of directly delivering the unprocessed EFB to the field.

The GHG emissions from biochar production are correlated with the energy inputs. The highest share of GHG emissions over the whole production chain stems from the pyrolysis process, due to intensive use of diesel fuel for the combustion of the EFB. GHG emissions in the reference systems with direct delivery of EFB to the field are 68% of the GHG emission in the studied case with biochar production, without taking into consideration GHG emissions from the soil with biochar. The total costs for the production, handling, transportation and delivery of biochar to the fields are nearly twenty times higher than the costs for the direct use of EFB to the fields. The high costs incurred with the production of biochar can only be balanced if the biochar is sold at a price of 533 US-$ t^{-1}.

The results of the financial analysis indicate that at a sales price for biochar of 533 US-$ t^{-1}, the *benefit–cost-ratio* (B/C-ratio) of the studied biochar production facility is above 1, the *net present value* (NPV) is positive, and the *internal rate of return* (IRR) is above the bank interest rate. The *payback period* (Pb) is shorter than the depreciation time generally assumed for machines and equipment and the yearly return on investment (RoI) is 17.60%. It may be concluded that under the present conditions the production of biochar from palm oil EFB, using slow pyrolysis in the facility in Malaysia, is technically feasible and economically viable. The sensitivity analysis suggests that the economic viability may get lost, if e.g. the price for EFB increases, the price for diesel fuel rises or the price for biochar falls.

In view of the energy demand, GHG emissions and economic risks associated with the operation of a facility such as the one studied in Selangor, Malaysia, it seems indispensable to increase the efficiency of biochar production from palm oil EFB. Therefore, we recommend investigating possibilities to reduce diesel fuel consumption and to make use of the byproducts from the pyrolysis process, such as the bio-oil.

Furthermore, research is needed to evaluate the soil-born GHG emissions from biochar of palm oil EFB in comparison to direct application of palm oil EFB. Finally, implications of biochar for nutrient availability in the soil and soil water-holding capacity, as well as for the soil biological health, need to be studied to assess the pros and cons of biochar production from palm oil EFB.

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