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Life cycle assessment and cost-benefit analysis of palm biorefinery in Thailand for different empty fruit bunch (EFB) management scenarios

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Abstract. Palm oil production has been growing over the past decade to fulfill the increased demands for vegetable oil and biodiesel. Along with crude palm oil production, a substantial amount of palm biomass is produced, inappropriate management of which would affect environmental performance, and consequently business competitiveness. Life cycle assessment (LCA) has been conducted to assess the environmental impacts of five different palm biorefinery scenarios for empty fruit bunch (EFB) management comparing them with the baseline scenario (i.e. mulching in oil palm plantations). The scenarios include (1) EFB and Palm Oil Mill Effluent (POME) co-compost and cogeneration, (2) EFB based ethanol production and cogeneration, (3) EFB briquette production and cogeneration, (4) EFB compost and cogeneration and (5) EFB cogeneration. The ReCiPe impact assessment methodology was used considering seven impacts categories, viz., global warming, acidification, freshwater eutrophication, marine eutrophication, photochemical oxidant formation, particular matter formation, and fossil depletion. The results revealed that the EFB and POME co-compost and cogeneration (Scenario 1), EFB compost and cogeneration (Scenario 4), and EFB cogeneration (Scenario 5) could help improve the environmental performance of the existing Thai palm oil industry. In terms of economic aspect, the cost-benefit analysis and net present value (NPV) were used to evaluate each scenario's investment. The EFB and POME co-compost production (Scenario 1), EFB briquette production (Scenario 3), EFB compost (Scenario 4) and EFB cogeneration (Scenario 5) were financially feasible. However, the Scenario 1 was recommended due to the least investment and operation costs and the highest NPV. The EFB based ethanol production (Scenario 2) was not financially feasible.

Keywords: Life Cycle Assessment, palm oil mill, biomass, biorefinery.

1. Introduction

Oil palm is one of the important crops which is recognized worldwide as a feedstock for various products such as cooking oil, oleochemicals, and biodiesel. The growing global demand for palm oil has led to an increase in oil palm plantation area and Fresh Fruit Bunch (FFB) production. From the year 2010 to 2017, the global oil palm plantation area increased by around 27% and the global FFB production also increased by 33%. Indonesia and Malaysia are the two largest producers; the combined palm oil production from those two countries accounting for about 85% of the world's palm oil production. Thailand is the third largest producer sharing about 3% of the total palm oil production [1]. In Thailand, oil palm is widely planted in the southern region of the country. The total oil palm plantation area in 2017 was around 756,630 ha, which has been increased from 2010 by around 40%. This was due to the growing demands for palm oil for domestic use i.e. food as well as use as a raw material for biodiesel industries. Around 14.6 million tonne of FFB were produced in 2017, which was an increase of about 77% from 2010 [1]. The increase in palm oil production resulted in the increased palm biomass generation.

Generally, at the palm oil mill, there are two main products, i.e. crude palm oil (CPO) and palm kernel, generated along with the palm biomass residues, i.e., empty fruit bunch (EFB), fiber, shell and decanter cake. On a mass basis, the products and residues generation per tonne of FFB processed include about 20% of CPO, 5% of palm kernel, 22-23% of EFB, 12-15% of fiber, 4-7% of shell, and 3.5% of decanter cake [2-5]). To produce a tonne of CPO, around 5-7.5 tonne of water is also required; about 50% of that water used will end up as the palm oil mill effluent (POME) [5-6]. Currently, most of the palm oil mills in Thailand have installed biogas capture systems and produce electricity to sell to the Provincial Electricity Authority (PEA). It was evaluated that this practice could reduce the greenhouse gas (GHG) emissions of the palm oil production system by around 30% as compared to the process without biogas capture [7]. Moreover, the treated POME can be used as a liquid fertilizer which increasing FFB production [8]. Fiber is used as a solid fuel for the in-house boiler to produce steam for the milling process. Palm shell is sometimes used partially as a fuel in the boiler. The rest of the shell is sold to the other industries to be used as solid fuel. EFB, the major biomass residues of the mill, is generally dumped or mulched in plantation or used for mushroom cultivation. Decanter cake is processed for producing animal feed [9-10].

Since the time environmental standards like ISO 14000 series were established, environmental performance has influenced business competition. In addition, many of the sustainability standards have also been launched such as Roundtable on Sustainable Palm Oil (RSPO), Renewable Energy Directive of the EU, Roundtable on Sustainable Biomaterials (RSB), and Global Bioenergy Partnership (GBEP) to drive the industries in moving towards sustainable production. There are several environmental challenges for the palm oil industry to handle, one of the major ones being waste management. The traditional waste management approach like end-of-pipe treatment should be changed. The palm oil mills nowadays try to cope with the palm biomass residues by creating additional value from them. Palm biomass residues are mostly lignocellulosic materials which can be further processed and used in a variety of applications. For example, EFB has been recommended to be used as a feedstock for ethanol production [11-12], briquette production [13], co-composting [14], and power generation [15]. Fiber can be used as feedstock for fiberboard; while the shell can be used as feedstock for biochar, activated carbon, and charcoal [16]. However, the different approaches of palm biomass residues management will require additional unit processes as well as the materials, chemicals, and energy which in turn may result in additional environmental impacts. For example, utilization of EFB as solid fuel requires the addition of the shredding process and transportation of EFB to the boiler. Co-composting of EFB with POME requires fuel for the mixing process. Thus, life cycle assessment is necessary to evaluate the environmental loads and potential environmental impacts associated with palm oil mills and their new approach for palm biomass residues management. The study, therefore, aims to explore the current EFB management practices and the capability of those practices for improving the environmental performance of the palm oil mills in Thailand. The different systems of the palm oil mill equipped with the various options of waste management and utilization for producing the new products are therefore evaluated using life cycle assessment. Moreover, the financial feasibility of each practice is evaluated using the net present value (NPV). The recommendations are expected to support the palm entrepreneurs' decision making in selection of EFB management options.

2. Materials and methods

Life cycle assessment (LCA) was applied to evaluate the environmental impacts of different palm biorefinery scenarios for EFB management i.e. EFB cogeneration, EFB briquette production, EFB composting and EFB based ethanol production. According to Saswattecha et al. (2016) [15], the use of EFB as a solid fuel for power generation could significantly reduce several environmental impacts of the palm oil production system such as acidification, eutrophication, and human toxicity, while, EFB as briquette or compost could bring about environmental benefits as well. Cellulosic ethanol production from EFB is also widely discussed to substitute the current first generation bioethanol production derived from food crops like sugarcane and cassava.

The ReCiPe methodology, an environmental impact assessment method widely used in LCA [17], was chosen to use in the study. The life cycle inventory (LCI) data from the investigated biorefinery includes the emissions of substances such as CO_2, CH_4, N_2O, NO_x, SO_x and particulate matter (PM) from palm biomass combustion, total N and total P from fertilizers used and composting process. Hence, there are several key environmental impacts categories relevant to the resources used and emissions considered, i.e. global warming, acidification, freshwater eutrophication, marine eutrophication, photochemical oxidant formation, particular matter formation, and fossil depletion.

The system boundary of the study was "cradle to gate" i.e., starting from oil palm cultivation, transportation of FFB to the mill, unloading the FFB into the ramp, sterilization of FFB, milling and using of palm biomass in view of biorefinery system. The unit of analysis is defined as 6,000 kg of FFB processed in the palm oil mill to generate CPO and palm kernel (PK). EFB, fiber, shell, decanter cake and POME are the by-products further managed as shown in the Fig. 1.

The composting, ethanol and briquette production will require the installation of additional equipment to the palm oil mill. Therefore, the return of investment of each EFB management scenario is evaluated by the NPV indicator. NPV is the difference between the present value of cash inflows and the present value of cash outflow over the study period. Equation (1) shows the formula to calculate NPV.

$$NPV = \sum_{t=1}^{n} \frac{Ct}{(1+i)^t} - C_0 \quad (1)$$

Where: C is the net cash inflow during a single period t
C_0 is the total initial investment cost
i is the discount rate, defined the discount rate about 10%
t is the period, for this study defined as ten years since 2018 - 2028

2.1 Data collection

In the assessment, the data collection was separated into three parts; firstly, data for oil palm cultivation was referred from Silalertruksa et al. (2017) and Gheewala (2015) [18-19]. Secondly, data for palm oil production was collected from six palm oil mills in Thailand including four mills in Krabi province and one mill in Surat Thani province in the south of Thailand, and one mill in Chonburi province in the east of Thailand. Thirdly, data for EFB management scenarios which were collected from both field data and literature. The inventory data for the EFB composting process was collected from two mills. The data for EFB cogeneration process was referred from one mill. Since the EFB briquette and the EFB based ethanol production are currently not available in Thailand, the inventory data for those were referred from the study of Chiew and Shimada (2013) and Jeon et al. (2014) [12, 20]. Air emissions factors related to all unit process, materials, and energy including CO_2 (biogenic), CH_4, N_2O, NO_x, SO_x and PM were taken from Ecoinvent (2013) [21], EEA (2016) [22], IPCC (2006) [23] and NREL (2013) [24]. The summary of LCI data sources for the production of materials, chemicals, and emissions of biomass combustion are shown in Table 1.

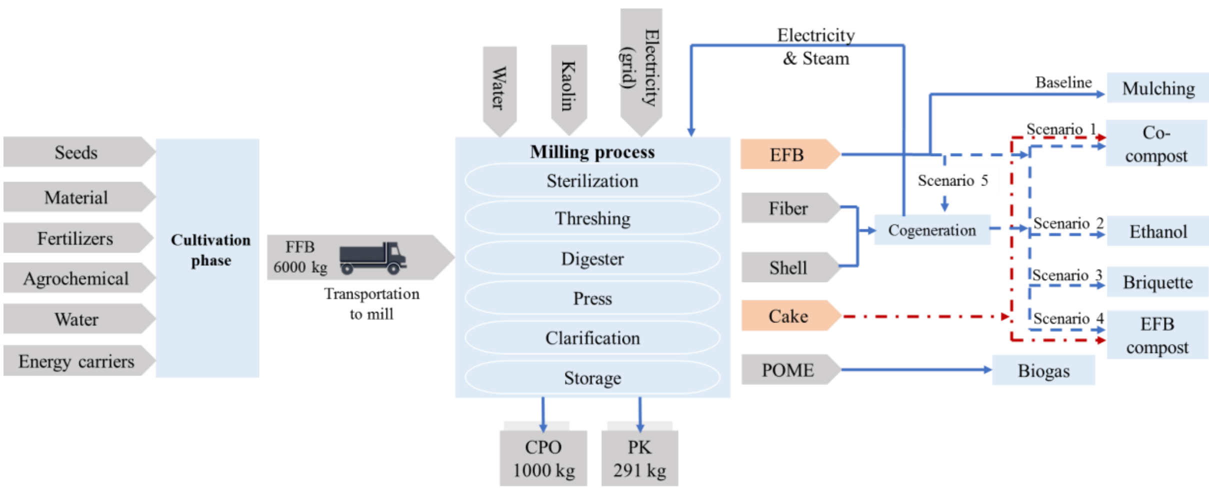

Figure 1. System boundaries of the palm oil biorefinery.

Table 1. The summary of data sources for this study.

Unit processes/materials	Activities	References
Oil palm cultivation - FFB	Production of FFB	[18-19]
Palm oil production		
1. Milling		
- Electricity grid	Production of grid electricity	[21]
- Kaolin	Production of kaolin	[21]
2. Steam and electricity generation		
- Fiber	Combustion of fiber	[22-23]
- Shell	Combustion of shell	[22-23]
3. Water treatment		
- Alum	Production of alum	[21]
- Polymer	Production of polymer	[21]
- Cl	Production of Cl	[21]
- NaCl	Production of NaCl	[21]
4. Wastewater treatment		
- POME	Anaerobic treatment of wastewater	[23]
Biorefinery concept		
- Diesel	Production of diesel	[21]
	Combustion of diesel	[21]
- NaOH	Production of NaOH	[24]
- Enzyme cellulase	Production of Enzyme cellulase	[24]
- EFB	Combustion of EFB	[22-23]

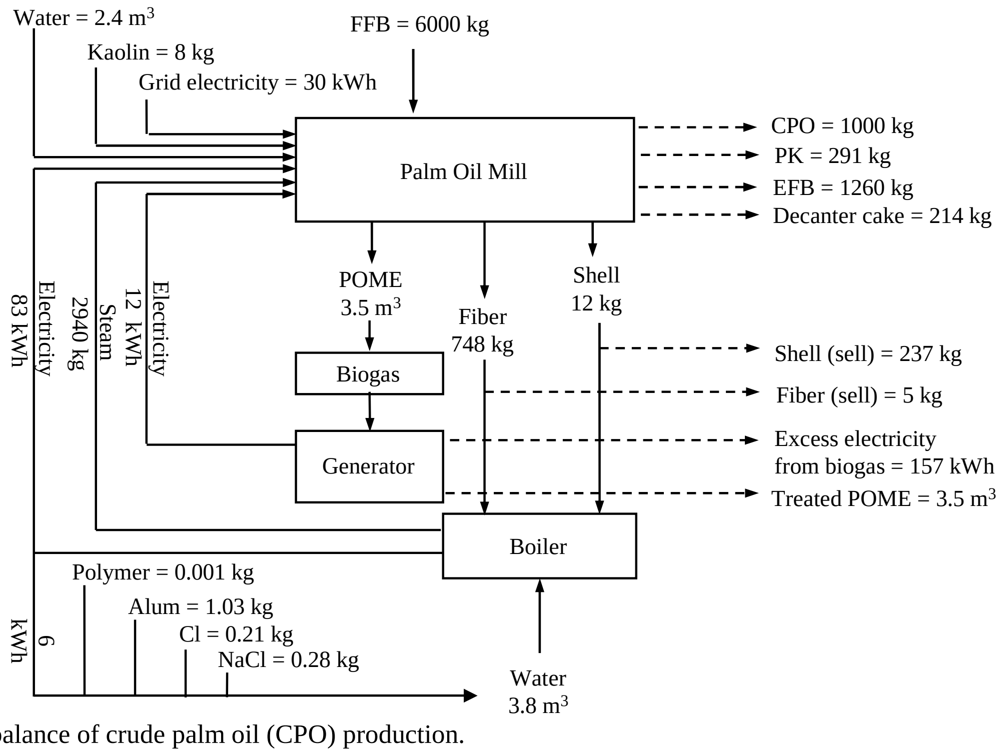

Figure 2. Mass balance of crude palm oil (CPO) production.

2.2 System description

2.2.1 Oil palm cultivation

Oil palm cultivation stage includes palm nursery, land preparation, selection of healthy seedling for planting, planting and replanting, treatment and harvesting, and transport. Water is very important especially in the stage of oil palm nursery. Fertilizers were applied since nursery and after the plantation. The production of a tonne FFB required 8 kg of N-fertilizer, 5 kg of P-fertilizer, 13 kg of K-fertilizer, 49 kg of organic fertilizer and 4 kg of soil conditioners [18]. Fuel used for machinery and transport consists of 2 liters of diesel, 1 liter of gasoline, 4 liters of gasohol and 0.5 kg of LPG for a tonne of FFB. Moreover, about 0.4 liters of agrochemical used for a tonne FFB production as well. The environmental impacts of FFB production are shown in Table S1 of the Supporting Information (SI).

2.2.2 Palm oil production

The production capacity of the studied mills ranged between 40-90 tonne FFB/hour. Oil extraction rate (OER) of the surveyed mills is 17%. The distance between oil palm plantations and mills was estimated to be about 5 km. The reference unit of assessment is defined as 6,000 kg of FFB processed into the mill which, in turn, generates CPO about 1,000 kg. Apart from the CPO, the milling process also generates about 291 kg of palm kernels, 1260 kg of EFB, 753 kg of fibers, 214 kg of decanter cakes and 248 kg of shells (Fig. 2). Palm kernel is considered as the co-product that will be further milled to produce the palm kernel oil. Around 3.5 m^3 of POME is generated as the wastewater and treated by the anaerobic cover lagoon with biogas capture. For the boiler unit, fiber and shell were used as fuels for steam and electricity generation; while, feed water used in the boiler also required the treatment before. The system boundary of assessment therefore includes the production and use of chemicals such as polymer, alum, chlorine, and sodium chloride for boiler feed water treatment. The boiler capacity of the studied mills is about 30-45 tonne/hour of steam (2-6 MPa). The steam turbine generator has a capacity of about 1.2 MW. Furthermore, around 8 kg of kaolin is used per 6,000 kg of FFB in the hydrocyclone process for separating the palm kernel from the shell. The LCI for the processing of 1000 kg CPO in each mill is presented in the Table S2 of the SI.

2.3 EFB management scenarios under the biorefinery concept

2.3.1 Baseline scenario

At present, EFB is generally sent to mulch in the oil palm plantation areas owned by the mills. The transportation of EFB from the mill to the plantation, around 5 km, is also accounted. About 748 kg of fibers and 12 kg of shells are used as solid fuel in the boilers at the mills to produce 2,940 kg of steam and 105 kWh of electricity (Fig. 2). The generated electricity from the boiler is used inside the factory for the milling process, office, and water treatment process. Nevertheless, the own-produced electricity used internally in the mill is not adequate. About 30 kWh of electricity from the grid is additionally required for the mill. The electricity produced from biogas capture during POME treatment is mainly sold to the PEA; only a small amount will be used in the mill. Shells and decanter cake are sold as fuel and animal feed, respectively.

2.3.2 Scenario 1: EFB and POME co-compost and cogeneration

In this scenario, EFB will be used for both electricity generation and composting. For the cogeneration system, about 748 kg of fibers, 15 kg of shells and 205 kg of shredded EFB are used as fuels to generate steam and electricity for internal use. Compared to the baseline, the additional electricity obtained from the utilization of EFB in the cogeneration system is subtracted by the additional electricity used in the system for shredding EFB and EFB compost. The electricity obtained from EFB can thus reduce the grid electricity consumption of the mills from 30 kWh (from baseline) to 17 kWh. Moreover, the composting technique has been added to produce fertilizer from EFB and decanter cake. For both cogeneration as well as composting, EFB needs to be pretreated by pressing and shredding. The EFB weight reduces from the initial 1260 kg (with 60% of moisture content) to 505 kg (with less than 10% of moisture content) after the pretreatment. The EFB pretreatment process consumes 13 kWh of electricity (based on 10.3 kWh electricity per 1000 kg EFB).

After the EFB pretreatment, the EFB is divided for two purposes. As mentioned above, about 205 kg of the pretreated EFB is used as fuel in the cogeneration. The remaining pretreated EFB of around 300 kg is used for composting. About 46 kg of decanter cake is added into the process, and 0.5 m^3 of the treated POME is sprayed. About 2 kWh of electricity is used for the aeration process during composting. At the end of this process, 115 kg of compost is produced. In summary, the palm biorefinery (Scenario 1) generates 1000 kg of CPO as the main product, and the co-products include 291 kg of palm kernel, 168 kg of excess decanter cake, 234 kg of excess shell, 5 kg of excess fiber, 157 kWh of excess electricity, and 115 kg of EFB and POME co-compost.

2.3.3 Scenario 2: EFB based ethanol production and cogeneration

The feedstocks used for the boiler and cogeneration system are the fiber, shell, and EFB which is the same as the Scenario 1. However, ethanol production from EFB is added to the system. In the production system, the EFB is shredded, separated and used for two purposes. For the first purpose, about 265 kg of shredded EFB is used as fuel for the cogeneration system along with 748 kg of fibers and 16 kg of shells. The generated electricity is used in the milling process, water treatment, shredder, and ethanol production at about 83, 8, 13 and 13 kWh, respectively. Nevertheless, the system still requires 20 kWh of the grid-electricity for running the process.

For the second purpose, about 240 kg of shredded EFB is further treated with 139 kg of sodium hydroxide (NaOH) for ethanol production. After that, the EFB is then hydrolyzed and fermented with 40 FPU/g cellulose and 5% of *Saccharomyces cerevisiae* (FPU stands for the filter paper unit which means of the amount of enzyme capable of releasing one micromole reducing sugar [25]). Energy consumption of the ethanol production process is around 13 kWh, and about 35 kg ethanol is obtained. In summary, the palm biorefinery system as Scenario 2 would generate the main product as 1000 kg of CPO, and co-products including 291 kg of palm kernel, 214 kg of excess decanter cake, 233 kg of excess shell, 5 kg of excess fiber, 157 kWh of excess electricity, and 35 kg of EFB based ethanol.

2.3.4 Scenario 3: EFB briquette production and cogeneration

Briquette production from EFB has been added in the system to substitute the composting and the ethanol production in Scenarios 1 and 2, respectively. In the system, around 630 kg of EFB is pretreated by the pressing and shredding units. After the pretreatment, the weight of EFB is reduced to around 252 kg with less than 10% moisture content. The pretreatment process consumes around 6 kWh. In this scenario, EFB is shredded and used only for the boiler. The amounts of fiber, shell, and shredded EFB used for the cogeneration are the same as in Scenario 2. The steam and electricity generated in the factory are used internally for the milling process, water treatment, EFB shredder, and EFB briquette production. Nevertheless, the electricity from the boiler is not sufficient for the EFB briquette production, and the use of electricity from biogas is required. The remaining 630 kg of EFB could be used as the raw material for briquette production. The EFB briquette production requires about 0.11 kg of diesel, 29 kWh of electricity for the production of 210 kg of EFB briquette. Accordingly, the products and co-products generated from the Scenario 3 are about 1000 kg of CPO as the main product, while, 291 kg of palm kernel, 5 kg of excess fiber, 214 kg of excess decanter cake, 234 kg of excess shell, 155 kWh of excess electricity, and 210 kg of EFB briquette are co-products.

2.3.5 Scenario 4: EFB compost and cogeneration

The system is like Scenario 1 but with a different technology used for fertilizer production. In Scenario 4, around 300 kg of EFB and 68 kg of decanter cake were composted in the ponds and then left as a pile to reduce the moisture. After that, it was sent as the feed to bio-mixer which is a machine for grinding and pelletizing the compost by using the granular fertilizer machine at 80ºC. The machine requires about 0.24 kWh of electricity to produce 141 kg of compost. The remaining 960 kg of EFB will be shredded and used as fuel for boiler together with 748 kg of fiber and 17 kg of shells. About 384 kg of shredded EFB remaining from this system can be used to produce electricity which will increase the electricity production by around 55 kWh as compared to the baseline scenario. The surplus electricity can be sold to the grid system. Hence, the products and co-products obtained from the Scenario 4 are main product 1000 kg of CPO, with 291 kg of palm kernel, 5 kg of excess fiber, 146 kg of excess decanter cake, 231 kg of excess shell, 168 kWh of excess electricity, 141 kg of EFB compost as co-products.

2.3.6 Scenario 5: EFB cogeneration

In Scenario 5, EFB is only used as fuel for electricity production. In the system, about 1260 kg of EFB is shredded requiring about 13 kWh of electricity. After the shredding process, about 505 kg of EFB (with less than 10% moisture content) is

Table 2. The co-products obtained from the studied biorefinery scenarios and their avoided products.

Scenario	Products	Quantity	Avoided products	Quantity
Baseline scenario	Electricity (biogas) (kWh) Shell (kg)[a]	157 237	Electricity (grid) (kWh) Bituminous coal (kg)[c]	157 152
Scenario 1	Electricity (biogas) (kWh) Shell (kg)[a] Compost (kg)[b]	157 234 115	Electricity (grid) (kWh) Bituminous coal (kg)[c] N -fertilizer (kg) P -fertilizer (kg) K -fertilizer (kg)	157 150 2.65 1.62 3.12
Scenario 2	Electricity (biogas) (kWh) Shell (kg) [a] Ethanol (kg)[d]	157 233 35	Electricity (grid) (kWh) Bituminous coal (kg)[c] Gasoline (L)[c]	157 149 31
Scenario 3	Electricity (biogas) (kWh) Shell (kg)[a] Briquette (kg)[e]	155 234 210	Electricity (grid) (kWh) Bituminous coal (kg)[c] Bituminous coal (kg)[c]	155 149 144
Scenario 4	Electricity (biogas) (kWh) Shell (kg) [a] Compost (kg)[f]	168 231 141	Electricity (grid) (kWh) Bituminous coal (kg)[c] N -fertilizer (kg) P -fertilizer (kg) K -fertilizer (kg)	168 148 2.85 1.27 3.23
Scenario 5	Electricity (biogas) (kWh) Shell (kg)[a]	182 229	Electricity (grid) (kWh) Bituminous coal (kg)	182 147

[a] calorific value from DEDE (2018) [26]
[b] nutrition of compost acquired from Chima and Umeh (2019) study [27]
[c] calorific value from Engineering ToolBox (2003) [28]
[d] calorific value from NPL (2017) [29]
[e] calorific value from Chiew and Shimada (2013) [20]
[f] nutrition of composed is factory-based analysis by 2.02% N, 0.9% P, 2.29 % K

obtained. This is used as fuel in the boiler along with the fiber (748 kg) and shells (19 kg) to produce electricity and steam. The product and co-products of this Scenario 5 include 1000 kg of CPO as the main product, and 291 kg of palm kernel, 5 kg of excess fiber, 214 kg of excess decanter cake, 229 kg of excess shell, 182 kWh of excess electricity as co-products.

2.4 Substitution and avoided products

The environmental impact potentials of each scenario are evaluated and presented based on the reference flow of about 6000 kg FFB processed in each biorefinery scenario. The substitution of the co-products of the biorefinery is considered. The electricity produced from biogas is supposed to substitute the grid-mix electricity of Thailand, the shells are supposed to substitute bituminous coal, the compost is used to substitute N-P-K chemical fertilizers, the ethanol is used to substitute conventional gasoline, and the briquettes are used to substitute bituminous coal. The substitution description of each scenario is shown in Table 2.

Scenario 3 has less grid electricity avoided than the other scenarios because the EFB briquette production requires 29 kWh of electricity which cannot be fully met by the electricity from the boiler. Thus, about 2 kWh of electricity from the biogas unit is provided to fulfill the deficit and the remaining electricity from biogas to substitute grid electricity is thus about 155 kWh. On the other hand, Scenarios 4 and 5 have about 11 and 25 kWh higher avoided electricity, respectively, than the baseline scenario because more EFB is used for electricity generation.

3. Results and Discussion

3.1 Environmental impacts of the biorefinery after accounting the environmental credits for EFB utilization

Fig. 3 shows the potential environmental impacts of the biorefinery after accounting the environmental credits for the EFB utilization in each scenario. These results are calculated based on Table S1 and S3 in the SI. The red line represents the net impact values of the baseline scenario. Fig. 3a reveals that Scenario 4 brought about the lowest global warming impact, i.e. 734 kg CO_2eq/reference unit (i.e. 6,000 t FFB processed), followed by Scenarios 1, 5 and 3, respectively (Table S3 of the SI). The main source of global warming in all scenarios is the FFB production (from the oil palm cultivation phase) sharing about 82-96%. The N_2O and CO_2 emitted as direct emission from the applied N-P-K fertilizers, and fuel in the plantation contribute about 49-60% of total global warming potential. The production of N-P-K fertilizers contributed about 37% with N-fertilizer production alone contributing 28%. The other contributors are the production of pesticide, soil amendment, tap water and fuel. On the other hand, Scenario 2 performed the worst. The global warming impact of the biorefinery system would increase as compared to the baseline scenario as well as the other scenarios. This implies that the credit obtained from EFB based ethanol would be lesser than the existing credit that the mills obtain from the excess electricity to substitute grid electricity. In addition to FFB production, the grid electricity used for the mill is a large contributor to global warming in all the scenarios. Especially for the Scenario 2, the ethanol production process requires substantial electricity consumption due to distillation and dehydration leading to high global warming contribution of this scenario. The ethanol production contributes about 148 kg CO_2eq to global warming in which 98% of the impact stems from the NaOH production.

The acidification impact potentials are shown in Fig. 3b. The results are almost the same in all scenarios because FFB production contributed about 99% of the total acidification impact in all scenarios (Table S1 of the SI). The major source of acidification impact in FFB production includes about 61% from NH_3 emission and 35% from the production of N-P-K fertilizer. Palm biomass combustion in the mill also emits the NO_x and SO_x. The co-products obtained at the mills in each scenario, i.e. compost, ethanol, electricity, briquette, and bituminous coal, can turn to only about 0.5-0.7 kg SO_2eq avoided emissions; which are very low when compared to emissions from FFB production (725 kg SO_2eq). Scenario 2 shows the highest acidification impact due to the additional impact of ethanol production process (i.e. NaOH used).

Freshwater eutrophication impact potentials are shown in Fig. 3c. Scenario 4 has the highest reduction of the eutrophication impact as compared to the baseline scenario, followed by Scenarios 5, 1, and 2, respectively. For the baseline scenario, the source of freshwater eutrophication is FFB production and the use of grid electricity. The FFB production is the main contributor to the total freshwater eutrophication impact in all scenarios sharing about 85-98%. The impact in FFB production is from the leaching of phosphate to river during the cultivation process contributing about 46-49%. In addition, the production of N-P-K fertilizer and pesticide shares about 19-23% as well. The significant improvement found in Scenarios 4, 5 and 1 were due to the production and use of the compost derived from the decanter cake to substitute chemical fertilizers and the use of bioelectricity from biomass and biogas.

NO_x emissions from EFB combustion in the boiler can contribute to the marine eutrophication impact. Nevertheless, the leaching of nitrogen from fertilizers during oil palm cultivation was the major source contributing about 99% of the total marine eutrophication impact potential. The avoided emissions from the co-products obtained in the scenarios are about 0.1-1 kg N eq which are not much when compared with the impact from the FFB production. Fig. 3d shows that there is no significant difference in the marine eutrophication impacts when comparing between the baseline scenario and the five scenarios of EFB management. The milling process contributes less than 1% of the total marine eutrophication impact; meanwhile, about 99% of the impacts are from the oil palm cultivation.

The results of photochemical oxidant formation and particular matter formation potential were identical for all the scenarios as shown in Fig. 3e and 3f. The impacts on photochemical oxidant formation and particular matter formation at about 66% and 53%, respectively, mainly came from the stage of production of N-P-K fertilizer, especially N-fertilizer. The other contributors from FFB production are from direct emission of NO_x emission at about 25%. For particular matter formation, direct emission of FFB production came from NH_3 emission at about 41%. The results revealed that there are no differences between the scenarios. Although the grid electricity could be avoided from the studied systems, but the biomass combustion in the boiler also leads to the CH_4 (biogenic), CO (biogenic), NO_2, NO_x, NMVOC, SO_x, PM_{10}, and $PM_{2.5}$ emissions which potentially affected both impacts.

Fig. 3g shows the fossil depletion potential; the Scenarios 1, 3, 4 and 5 can help reduce the fossil depletion impact as compared to the baseline due to the reduction of grid electricity used in the palm biorefinery system. Another credit stems from the selling of shells to the other industries which generally use shells to substitute the imported bituminous coal. The only exception is the Scenario 2 where the EFB based ethanol production is energy intensive resulting in the higher net fossil depletion potential impact as compared to the baseline scenario. The summary of the environmental impact potential values are shown in the Tables S1 and S3 of the SI.

3.2 Financial feasibility analysis of the EFB management scenarios

The EFB and POME co-compost production (Scenario 1), the EFB based ethanol production (Scenario 2), the EFB briquette production (Scenario 3) and the EFB compost production (Scenario 4) are considered as the new processes which would be installed to the palm oil mill. Although for the EFB cogeneration (Scenario 5), the same boiler of the palm oil mill can be used; however, EFB shredder would be required to pretreat the EFB before loading it into the boiler. Thus, the costs, benefits and NPV of the new EFB scenarios were analyzed for evaluating the financial feasibility of the investments for those scenarios. The assumptions of each scenario investment is shown in Table S4 in SI. The cost of the EFB composting plant (Scenarios 1 and 4) are estimated from based on a pilot plant in a factory in Krabi province. The plant capacity is about 25 tonne compost per day (Scenario 1) and 20 tonne compost per day (Scenario 4) operating 300 days per year. On the other hand, Scenario 2, 3 and 5 are referred from literature. The cost of the EFB based ethanol plant (Scenario 2) is calculated based on the cost model of the lignocellulosic ethanol plant of Kaylen et al. (2000) [30]. The EFB briquette plant (Scenario 3) cost is calculated based on the EFB briquette plant with a capacity of about 4.35 tonne/hour with 7116 hours operation per year [15]. The salvage values are not accounted in all scenarios.

Table 3 shows the results on the costs, benefits and NPV of the five different EFB scenarios. The positive NPV indicates that the investment would be profitable. The NPV of the EFB based ethanol production (Scenario 2) is about -4,872 US$/tonne EFB, due to the high investment as well as high operation and maintenance costs of the lignocellulosic ethanol process as compared to the benefit obtained. This pointed that, although the lignocellulosic ethanol i.e. ethanol derived from the agricultural residues is expected as the promising option to avoid the problem on food-fuel competition due to the first generation bioethanol production in Thailand like the cassava ethanol and molasses ethanol [31], however, ethanol production from EFB (Scenario 2) is not feasible.

It can be seen that Scenarios 1, 3, 4 and 5 obtain the positive NPV which indicates that these options are feasible. The highest NPV is obtained for the Scenario 1 at about 239 US$/tonne EFB followed by the Scenarios 4, 5 and 3, respectively. The EFB compost production (Scenario 4) shows the highest investment cost, while the EFB cogeneration (Scenario 5) shows the highest operation and maintenance cost. Nevertheless, the EFB compost production (Scenario 4) would yield the highest revenue when compared with the Scenarios 1, 3 and 5.

The Scenarios 1 and 4 have the first and second highest NPV values. However, nowadays the substitution of chemical fertilizers by compost is not widely recognized by the palm growers due to its slow effects to the FFB productivity compared to the application of chemical fertiliers. Additionally, a large amount of compost would be required in the field in order to substitute the same amount of N-P-K nutrients provided by the chemical fertilizers. Hence, the cost of palm growers might be increased. Nevertheless, there are studies showing that the compost should be promoted to palm growers due to its long-term benefits such as the increased productivity and soil quality [32].

The EFB briquette production (Scenario 3) offers many benefits. Although it is generally used in small scale, like the household, for cooking stoves and restaurants; however, it can also be used in larger scales for the industrial boilers to produce heat, steam, and power. For example, briquette can substitute coal in the power plant. The prices of EFB briquette and bituminous coal are 53 US$/tonne of EFB briquette (or 2.94 US$/GJ EFB briquette) and 75.9 US$/tonne of bituminous coal (2.88 US$/GJ bituminous coal). Thus we can see that on an energy basis, the prices of EFB briquette and bituminous coal are almost the same. Substitution of this fossil fuel by EFB briquette may reduce the adverse effects of fossil fuel use. Furthermore, the use of briquette could help decrease the wood logging for wood burning stoves [33].

Table 3. The costs, benefits and NPV results for the investment of Scenarios 1-5 (calculated as per a tonne EFB)

Options	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Cost						
- Investment	US$/tonne EFB	35	2,156	32	363	13
- Operation and maintenance	US$/tonne EFB	3	541	10	1	14
Benefit	US$/tonne EFB	48	185	18	96	31
NPV	US$/tonne EFB	239	(4,872)	15	219	95

(…) refers to negative values

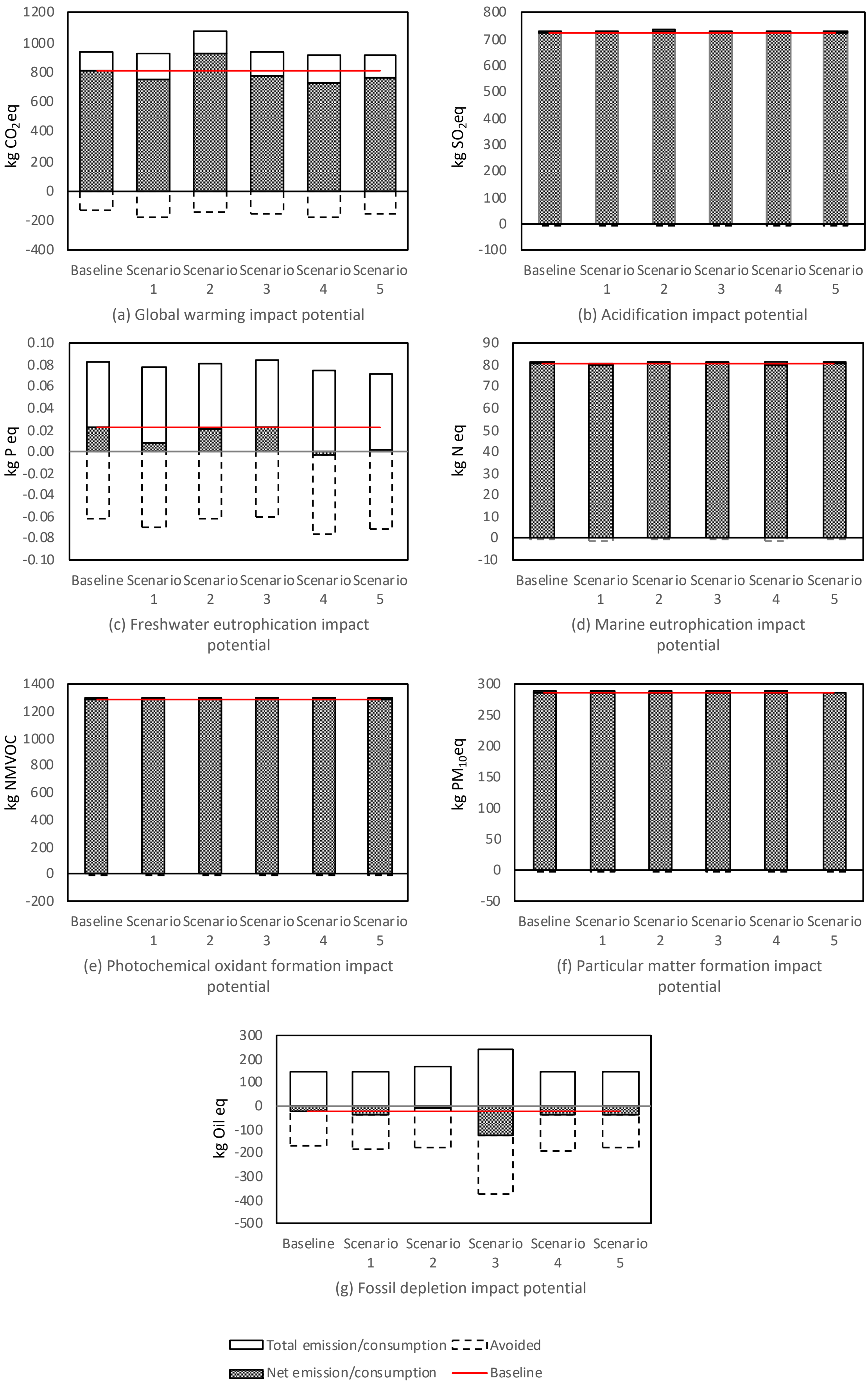

Figure 3. Environmental impact potential of 6000 kg FFB processed.

4. Conclusions

The study evaluated the environmental sustainability and the financial feasibility of palm biorefinery systems in Thailand based on the five different EFB management scenarios comparing with the baseline scenario (i.e. EFB is used to mulch in palm oil plantation). The five scenarios consist of Scenario 1: EFB and POME co-compost and cogeneration, Scenario 2: EFB based ethanol production and cogeneration, Scenario 3: EFB briquette production and cogeneration, Scenario 4: EFB compost and cogeneration, and Scenario 5: EFB cogeneration. The LCA results revealed that EFB compost and cogeneration (Scenario 4) resulted in a high potential to reduce the global warming and freshwater eutrophication impacts. The EFB briquette production and cogeneration (Scenario 3) should be recommended for the fossil depletion impact reduction. The Scenario 2 has shown the lowest environmental performances because most of the environmental impact potentials would be increased as compared to the baseline scenario. This was due to the environmental impacts from energy and chemicals used in the EFB based ethanol production process. The financial feasibility of those five scenarios is evaluated by using the cost, benefit and NPV. The results showed that the Scenarios 1, 3, 4 and 5 are financially feasible for the investment. The Scenario 1 could be recommended due to the least investment and operation costs and the highest NPV. The EFB based ethanol production (Scenario 2) was not financially feasible. The detailed practice for each EFB management practices used, advantages and limitations are also discussed for supporting the decision making of the palm millers.

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Supporting Information

Life Cycle Assessment and Cost-Benefit Analysis of Palm Biorefinery in Thailand for different Empty Fruit Bunch (EFB) Management Scenarios

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Table S1. Environmental impact potential classified by sources.

Environmental impacts	**Baseline Scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Global warming (kg CO_2eq)						
FFB	887	887	887	887	887	887
Kaolin production	1.8	1.8	1.8	1.8	1.8	1.8
Electricity grid mix, TH	21	12.2	14.3	21	-	-
Cogeneration	6.3	6.6	6.4	6	7.1	7
Biogas unit	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Transportation	22.4	19.1	19.1	19.1	19.1	19.1
Co-compost	-	0.4	-	-	-	-
EFB Ethanol	-	-	148	-	-	-
EFB Briquette	-	-	-	1.18	-	-
EFB compost	-	-	-	-	0.01	-
Total	939	927	1077	936	915	915
Environmental impacts	**Baseline Scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Acidification (kg SO_2eq)						
FFB	725	725	725	725	725	725
Kaolin production	0.01	0.01	0.01	0.01	0.01	0.01
Electricity grid mix, TH	0.08	0.04	0.05	0.08	-	-
Cogeneration	1.04	1.07	1.04	0.98	1.15	1.13
Biogas unit	0.07	0.07	0.07	0.07	0.07	0.07
Transportation	0.14	0.12	0.12	0.12	0.12	0.12
Co-compost	-	0.06	-	-	-	-
EFB Ethanol	-	-	1.28	-	-	-
EFB Briquette	-	-	-	0.18	-	-
EFB compost	-	-	-	-	0.002	-
Total	727	727	728	727	727	727
Environmental impacts	**Baseline Scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Freshwater eutrophication (kg P eq)						
FFB	0.07	0.07	0.07	0.07	0.07	0.07
Kaolin production	0.001	0.001	0.001	0.001	0.001	0.001
Electricity grid mix, TH	0.01	0.01	0.01	0.01	-	-
Cogeneration	0.0005	0.001	0.001	0.001	0.001	0.001
Biogas unit	0	0	0	0	0	0
Transportation	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Co-compost	-	0.00003	-	-	-	-
EFB Ethanol	-	-	0.002	-	-	-
EFB Briquette	-	-	-	0.0001	-	-
EFB compost	-	-	-	-	0.000001	-
Total	0.083	0.078	0.082	0.083	0.072	0.072
Environmental impacts	**Baseline Scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Marine eutrophication (kg N eq)						
FFB	80.6	80.6	80.6	80.6	80.6	80.6
Kaolin production	0.003	0.003	0.003	0.003	0.003	0.003
Electricity grid mix, TH	0.01	0.01	0.01	0.01	-	-
Cogeneration	0.07	0.07	0.07	0.06	0.08	0.07
Biogas unit	0.003	0.003	0.003	0.003	0.003	0.003
Transportation	0.01	0.01	0.01	0.01	0.01	0.01
Co-compost	-	0.004	-	-	-	-
EFB Ethanol	-	-	0.02	-	-	-
EFB Briquette	-	-	-	0.01	-	-
EFB compost	-	-	-	-	0.0001	-
Total	80.7	80.7	80.7	80.7	80.7	80.7

Environmental impacts	Baseline Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Photochemical oxidant formation (kg NMVOC)						
FFB	1288	1288	1288	1288	1288	1288
Kaolin production	0.01	0.01	0.01	0.01	0.01	0.1
Electricity grid mix, TH	0.04	0.02	0.03	0.04	-	-
Cogeneration	1.78	1.84	1.78	1.68	1.97	1.93
Biogas unit	0.001	0.001	0.001	0.001	0.001	0.001
Transportation	0.26	0.22	0.22	0.22	0.22	0.22
Co-compost	-	0.1	-	-	-	-
EFB Ethanol	-	-	0.67	-	-	-
EFB Briquette	-	-	-	0.31	-	-
EFB compost	-	-	-	-	0.003	-
Total	1290	1290	1290	1290	1290	1290
Environmental impacts	**Baseline Scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Particular matter formation (kg PM_{10}eq)						
FFB	284	284	284	284	284	284
Kaolin production	0.003	0.003	0.003	0.003	0.003	0.003
Electricity grid mix, TH	0.02	0.01	0.02	0.02	-	-
Cogeneration	0.95	0.97	0.94	0.89	1.04	1.03
Biogas unit	0.01	0.01	0.01	0.01	0.01	0.01
Transportation	0.05	0.04	0.04	0.04	0.04	0.04
Co-compost	-	0.06	-	-	-	-
EFB Ethanol	-	-	0.39	-	-	-
EFB Briquette	-	-	-	0.16	-	-
EFB compost	-	-	-	-	0.001	-
Total	285	285	286	285	285	285
Environmental impacts	**Baseline Scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Fossil depletion (kg oil eq)						
FFB	102	102	102	102	102	102
Kaolin production	0.5	0.5	0.5	0.5	0.5	0.5
Electricity grid mix, TH	6.4	3.7	4.4	6.4	-	-
Cogeneration	0.34	0.38	0.37	0.35	0.42	0.43
Biogas unit	0	0	0	0	0	0
Transportation	7.7	6.6	6.6	6.6	6.6	6.6
Co-compost	-	0.02	-	-	-	-
EFB Ethanol	-	-	47.5	-	-	-
EFB Briquette	-	-	-	0.2	-	-
EFB compost	-	-	-	-	0.001	-
Total	117	114	162	116	110	110

Table S2. Input and output per tonne of CPO production in each mill.

Input/output	Units	Mill 1	Mill 2	Mill 3	Mill 4	Mill 5	Mill 6
Input							
Materials							
FFB	kg	6930	6290	5950	5940	6100	5650
Kaolin	kg	11	15	10	11	10	1.3
Water	m^3	1.04	4.7	2.8	4.4	2.4	0.9
Energy							
Electricity (grid)	kWh	26	10	24	10	13	55
Electricity (boiler)	kWh	105	85	75	91	72	80
Electricity (biogas)	kWh	35	21	34	9	0	0
Steam	kg	4260	2940	3640	2990	2430	2470
Output							
Crude palm oil	kg	1000	1000	1000	1000	1000	1000
Palm kernel	kg	129	342	297	300	352	290
EFB	kg	1390	1109	1190	1200	1350	1310
Fiber	kg	0	0	38	0	0	0
Shell	kg	277	377	383	337	345	74
Decanter cake	kg	208	241	237	212	305	169
Treated POME	m^3	3.1	3.9	4.3	4.9	2.8	2.8
Electricity	kWh	89	681	109	206	106	5

Table S3. The summary of environmental impact potentials.

Environmental impacts	**Baseline scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Global warming (kg CO_2eq)						
- Emission	939	927	1077	936	915	915
- Avoided	-135	-172	-147	-157	-182	-152
- Net Emission	803	755	930	779	734	763
Acidification (kg SO_2eq)						
- Emission	727	727	728	727	727	727
- Avoided	-1	-1	-1	-1	-1	-1
- Net Emission	726	726	727	726	726	726
Freshwater eutrophication (kg Peq)						
- Emission	0.08	0.08	0.08	0.08	0.07	0.07
- Avoided	-0.06	-0.07	-0.06	-0.06	-0.07	-0.07
- Net Emission	0.02	0.01	0.02	0.02	0	0
Marine eutrophication (kg N eq)						
- Emission	80.7	80.7	80.7	80.7	81	80.7
- Avoided	-0.1	-1	-0.1	-0.1	-1.1	-0.1
- Net Emission	80.6	80	80.6	80.6	80	80.6
Photochemical oxidant formation (kg NMVOC)						
- Emission						
- Avoided	1290	1290	1290	1290	1290	1290
- Net Emission	-0.3	-0.4	-0.4	-0.3	-0.4	-0.3
	1289	1289	1290	1290	1289	1289
Particular matter formation (kg PM_{10}eq)						
- Emission						
- Avoided	285	285	286	285	285	285
- Net Emission	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2
	285	285	285	285	285	285
Fossil depletion (kg oil eq)						
- Consumption	117	114	162	116	110	110
- Avoided	-143	-148	-170	-244	-149	-144
- Net consumption	-25	-34	08	-127	-39	-35

Table S4. The assumptions of each scenario investment.

Item	Unit	Quantity	Cost (US$/unit)	Total cost (US$)	Depreciation	References
Scenario 1: EFB co-composting plant						
1. Land	ha/year	0.32	977	313	-	-
2. Mill	m^2	2,400	244	585,000	3% per year	Thai Appraisal Foundation (2018)
3. Equipment						
3.1 Tractor	cars	1	47,969	47,969	1.5% per year	Natthakit (2014)
3.2 EFB Shredder	machine	1	56,000	56,000	6.6% per year	Saswattecha et al. (2016) [15]
3.3 Pipe	m	100	27	2700	-	-
4. Electricity consumption	kWh/year	505,040	0.1	48,938	-	MEA (2019)
5. Labor	persons/year	4	3,600	14,400	-	MOL (2017)
6. Maintenance	US$/year	-	1,680	1,680	-	Saswattecha et al. (2016) [15]
Scenario 2: EFB ethanol plant						
1. Land	ha/year	3.2	977	3125	-	-
2. Initial investment	US$	-		9,249,851	-	Kaylen et al. (2000) [30]
3. Operation and maintenance	US$/year	-	2,319,729	2,319,729	-	Kaylen et al. (2000) [30]
Scenario 3: EFB briquette plant						
1. Land	ha/year	3.2	977	3125	-	-
2. Plant	-	1	2,934,904	2,934,904	6%	Saswattecha et al. (2016)
3. Operation and maintenance	US$/year	-	928,159	928,159	-	Saswattecha et al. (2016)
Scenario 4: EFB composting plant						
1. Land	ha/year	1.6	977	1563	-	-
2. Mill	m^2	16,000	244	3,900,000	3% per year	Thai Appraisal Foundation (2018)
3. Compost Machinery	machine	1	781,250	781,250	-	MOST (2010)
4. Electricity consumption	kWh/year	7,871	0.1	763	-	MEA (2019)
5. Labor	persons/year	4	3,600	14,400	-	MOL (2017)
Scenario 5: EFB cogeneration plant						
1. Equipment						
1.1 EFB shredder	machine	1	56,000	56,000	6.6% per year	Saswattecha et al. (2016) [15]
2. Electricity consumption	kWh/year	435,258	0.1	42,177	-	-
3. Labor	persons/year	4	3,600	14,400	-	MOL (2017)
4. Maintenance	US$/year	-	1,680	1,680	-	Saswattecha et al. (2016) [15]

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