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LCA METHODS TO COMPARE TREATMENT OPTIONS ON BIOMASS RESIDUES PRODUCED IN A PALM-OIL SYSTEM

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ABSTRACT

Palm oil systems generate large amounts of biomass residues. According to best agricultural practices, they are supposed to be returned back to plantation to maintain soil fertility. However, there are variations in practice. Differences in economic status and treatment options on biomass residues cause variations on the preference to perform LCA, leading to divergence in results that complicate interpretation. Difficulties found in comparing LCA results based on literature are not unusual. The objective of the paper is to provide guidelines on methodological choices to systematically compare diverse scenarios on the treatment and valuation of EFB (Empty Fruit Bunches) and to explore their effects on the environmental performances of a palm oil system.

Eleven scenarios were chosen to cover possible EFB valuation and expanded system boundaries with reference to the main palm oil system (application as mulch, conversion to compost or ethanol, treatment in an incinerator, and EFB as direct co-products). The life cycle inventories were modeled based on Ecoinvent database. The input EFB was considered either as wastes or goods, and the resulted products were used internally or externally. Solution to multi-functional problems was suggested, including the application of system expansion, substitution, and partitioning depending on the nature of the scenario.

The contribution of the plantation phases on global warming impact was so dominant that the effect of different scenarios could be observed only when focusing on the oil mill stage. Comparison among LCA results based on the same multi-functional units (crude palm oil + palm kernel oil + palm kernel cake) can be done only in the cases where additional co-products (mulch, compost, or ethanol) were used internally. Based on global warming impact, the mulch option was the best choice as compared to the compost, ethanol, or incineration options. The effect of the avoided process of producing substituted fertilizers was dominant in this comparison result. This study also demonstrates that the status of EFB as wastes or goods is influential to the final results when the EFB is used externally, but has no effect when it is used internally.

The proposed guidelines provide methodological choices in terms of system boundary, functional unit, and solution to multi-functional problems. The methods can be used to systematically compare LCA results of different treatment options and valuation of EFB. The best alternative in handling biomass residues could improve environmental performances of the palm oil system and orient towards best practices, such as those suggested by the Roundtable on Sustainable Palm Oil. Further studies using a specific case of palm oil systems would better illustrate the usefulness of the proposed guidelines. Although the approach was illustrated for a palm oil system, it is also readily applicable for handling biomass residues in other agro-based industrial systems.

INTRODUCTION

1. Palm oil and sustainability

Elaeis guineensis is a tropical forest palm native to West and Central Africa. It produces 3–8 times more oil for a given area than any other tropical or temperate oil crops (Sheil et al, 2009). Palm oil is a highly productive business in large scale and commercially profitable because demand for edible oils and biofuels is globally rising (Sheil et al, 2009). Indonesia has become the world's largest palm oil producer with about 21 million tonnes produced in 2009. Indonesia and Malaysia produced together around 87% of the global palm oil (Stichnothe & Schuchardt, 2011). However, the sustainability of oil palm cultivation and the production of palm oil have come under increasing scrutiny, particularly in relation to impacts on global warming as a consequence of massive land use changes (Koh & Ghazoul, 2010). In this regard, the Roundtable on Sustainable Palm Oil (RSPO) was established in 2003 (legally registered in 2004) to promote the use of sustainable palm oil through a voluntary certification scheme and to identify ways leading to environmental improvement (Laurance et al, 2010). Among promoted good practices, optimized land use change and proper management of biomass residues have been identified as potential instruments to improve sustainability in the life cycle of palm oil systems (Hansen et al, 2012).

2. Potential of solid biomass residues and treatment options

The oil palm biomass comprises fronds, leaves, trunks, root, fruit bunches, and inflorescences, while only about 10% of it yield in palm oil and palm kernel oil (Lee & Ofori-Boateng, 2013). Fronds and trunks are generated in plantation areas from periodic harvesting of fresh fruit bunches (FFB) and periodic re-planting of old palm trees, respectively. The cumulative amount of fronds for 23 years of productive period of a palm tree is about 1.8 tonnes on dry weight basis, and total biomass that fell during replanting is about 0.71 tonnes of trunk and fronds per palm (Yusoff, 2006). The exact amount will greatly vary with the planting material and field management. In 2011, Indonesia and Malaysia generated nearly 182 million dry tonnes of oil palm solid biomass which is projected to increase to about 230 million tonnes by 2020 (MPOB, 2012). Palm oil mills also leave behind large portion of biomass residues. For example, 1 ton of FFB on wet basis results in 0.220 tonnes of empty fruit bunch (EFB), 0.135 tonnes of mesocarp fiber, and 0.055 tonnes of palm kernel shell (Yusoff, 2006).

Press fiber and shell are commonly used as solid fuels for steam boilers to generate electricity and meet the internal energy demand for the operation of the palm oil mill, often located in remote areas far from national grids (Stichnothe and Schuchardt, 2011).

From the perspective of best agricultural practices, fresh EFB are preferably returned back to plantation as mulch to maintain soil fertility (Salétes et al, 2004). This closed-loop nutrient cycle can reduce the need for external fertilizers resulting in an efficient palm oil system. However, the distance between oil mills and plantation may become the limiting factor for the feasibility of the land application. Indeed, fresh EFB which are wet, bulky, and voluminous are unfavorable for handling and transportation. Consequently, there are variations in practice. Some of the EFB may be further processed into bioenergy, converted to compost, sold as direct co-products, or incinerated with or without energy recovery. These various treatment options are more likely to occur in oil mills with limited or no plantation areas. Such oil mills typically process FFB from other plantations.

The interest to convert biomass residues into other valuable products is also increasing (Stichnothe & Schuchardt, 2010; Hansen et al, 2012; Chiew & Shimada, 2013; Tuck et al, 2012). Some of them are directed towards bioenergy development (Lim & Lee, 2011; Wiloso et al, 2012; Chiew & Shimada, 2013). In Malaysia for instance, the Small Renewable Energy Power Program (SREP) was launched in Malaysia in 2001 to encourage utilization of agriculture residues to generate electricity to be connected to the national grid. This policy has attracted investments to develop combined heat and power plants (CHP) using palm oil biomass residues, including EFB. Some of them were installed at the palm oil mills and some were independent power plants connected to the grid. So far, there were 3 CHP plants operating from 1 to 14 MW as reported under the SREP program (Chiew & Shimada, 2013). In Indonesia, the Government has also recently issued new regulations on electricity price of bioenergy-based power plants (Kusdiana, 2013). In the last ten years, there were 10 on-grid power plants based on palm oil residues with contracted capacity between 2 to 10 MW. However, not all of them are continuously in operation. The main issues are the increasing price and continuous supply of biomass feedstock (Kusdiana, 2013).

Given the large amounts and the diversity of oil palm biomass residues, potential use and valuation ways are numerous and may provide economic and environmental benefits. However, most of the palm oil producers have not yet had a specific directive for choosing which technology is most environmentally suitable for their biomass residues. Some of them still continued practicing the old disposal method, such as dumped and burned (Chiew & Shimada, 2013).

3. Valuation of biomass residues

The common criteria in the valuation of biomass residues are that co-products provide relatively similar proceeds as the main-product, while by-products have a much lower value than co-products, and wastes have a negative value, i.e. treatment costs not offset by further valuation (Singh et al, 2010). However, in LCA community, by-products are typically not differentiated from co-products. Rather, all economic outputs besides the main product are considered as co-products with different values. Co-products become a generic term that encompasses all potential outputs from a process. Adopting this view, the system boundary of a palm oil system has to include all generated biomass residues throughout the process chains. Therefore, in addition to trunks, fronds, and inflorescences from the plantation, POME, shell, fiber, and EFB from the oil mills are also to be included in the life cycle inventory (LCI).

Economic flows in LCA travel between two unit processes, so each economic flow must be the output of one process or the input of another process (Heijungs and Frischknecht, 1998). The economic value of flows can be used as a criterion to determine the status of biomass residues (as goods or wastes). Guinée et al (2009) define products as having a positive economic value, whereas wastes have a negative economic value. More specifically, products in the LCA terminology include goods, energy, or services (Guinée et al, 2009). In the current paper, we considered EFB either as wastes or goods, depending on the specific conditions of the scenarios.

The process following a waste flow can be either a treatment unit to reduce the pollution strength of the waste or a conversion unit to make another product. The latter process provides both a waste treatment function and a function aimed at producing a certain product (Bellon-Maurel et al, 2013). In the context of defining system boundary, a waste stream is conventionally assumed to be free of environmental burden. The impact is charged entirely to the products and co-products preceding the waste stream. It means that actors in the upstream chain have to pay for the treatment or for getting rid of the waste stream.

There are quite a few cases where we do not know for certain if the price of an agricultural residue is positive or negative. Due to technological developments, fluctuations in markets, and governmental policy, wastes may rapidly turn into goods or the other way around. Also, depletion of natural resources has encouraged recycling of wastes for useful products. These developments may strongly affect valuation of biomass residues in a palm oil system. For the moment, the EFB may not have yet a real market value, but in the future it may become valuable. EFB has been raising interest as a potential feedstock for bioenergy (Lim & Lee, 2011; Wiloso et al, 2012; Chiew & Shimada, 2013), but LCA studies dealing with biomass residues at different valuation schemes are so far lacking. This paper intends to fill the gap.

4. Multi-functionality and burden allocation

A multi-functional process is a unit process yielding more than one functional flow. One way to solve multi-functional problem is by partitioning methods. It artificially splits the multi-functional process into a number of independently operating mono-functional processes (Heijungs & Guinée, 2007). The emissions will decrease, but the functional unit is not changed. There are different types of multi-functional processes depending on specific situations, i.e. co-production, recycling, and combined waste processing (Guinée et al, 2004). Co-production has more than one functional outflow and no functional inflow. Recycling has one or more functional outflows and one or more functional inflows. It reduces potentially harmful emissions from a waste and at the same time results in a useful product. Combined waste processing has no functional outflow, but more than one functional inflow. The application of the above concept on the diverse ways in handling biomass residues in an agricultural system are illustrated in Figure 1 (based on Wiloso & Heijungs, 2013). If the biomass residues are valued as goods or wastes (cases a and c), the environmental burden is partitioned between product1 and product2 or waste1 and waste2, respectively. If the biomass residues valued as wastes are converted to products (case b), the environmental burden is to be partitioned between the upstream (waste input) and downstream (product output) links. The partitioning factors can be based on different principles: physical properties or economic values of the functional flows. The physical properties can be based on the relative mass, carbon content, or energy content, while economic values are based on the relative market value of the functional flows.

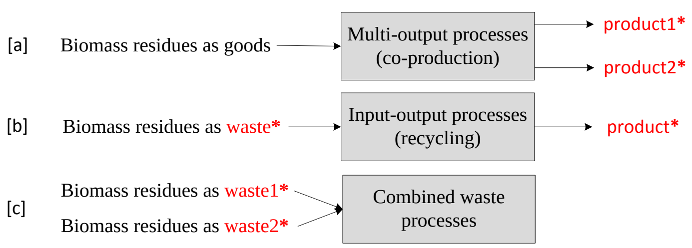

*Figure 1: Status of biomass residues and possible multi-functional processes. The last case (combined waste processes) does not yield products, but emissions. (*in red = functional flow).*

The ISO standard (ISO, 2006) prefers to avoid the above allocation methods in dealing with multi-functional problems. The priority is to divide processes into sub-processes, or by expanding the boundary of the product system. System expansion includes a co-product as an additional function to a product system. The resulted expanded system therefore consists of more than one functional flow. It changes the original functional unit into a new functional unit with two or more products, but the emissions do not change. The ISO standard mentions system expansion and partitioning, but does not mention substitution, also called subtraction or avoided burdens (Heijungs, 2014). However, almost all guidelines mention substitution.

The term system expansion is often mixed-up with the substitution method. Both approaches deal with multi-functional problems, but are manifested in quite different ways. Substitution adds an avoided process to the system that exactly cancels the co-product. The production of a co-product by the system under study causes another production process in another system to be avoided. This avoided production process results in avoided emissions that should be subtracted from the studied product system (Wardenaar et al, 2012). These different approaches (system expansion, partitioning, and substitution) were adopted in the current paper to deal with multi-functional problems in a palm oil system (see methodology section, Table 1).

5. Objective of the paper

There is an increasing interest in utilizing EFB in palm oil systems as feedstock for useful products. The pace of LCA research in the area of co-product valuation is also accelerating. However, these developments are not without problems. ISO 14044 leaves too much room in terms of methodological choices to perform LCA (Heijungs & Guinée, 2007). In addition, variation in the valuation of biomass residues as goods or wastes potentially adds to the overall complexity. Diversity in treatment options on biomass residues, which is particularly high in the case of palm oil system, may also cause variations in the preferences to perform LCA, leading to divergence in results. Meanwhile, to choose sustainable options, valid and consistent methodology is required. The above discussion brings to an important research question as how to properly assess and compare the effect of different treatment options and valuation of EFB on the performance of a palm oil system. The objective of the paper is to provide guidelines on methodological choices to systematically compare diverse scenarios on the treatment and valuation of EFB and to explore their effects on the environmental performances of a palm oil system. Methodological choices in terms of system boundary, functional units, and solution to multi-functional problems are suggested and their implementations on various scenarios illustrated.

METHODS

The LCI models were developed to represent a palm oil system integrated with various options in handling EFB. Eleven scenarios were chosen to cover possible EFB valuation (as goods or wastes) and expanded system boundaries with reference to the main palm oil system (application as mulch, conversion to compost or ethanol, treatment in an incinerator, and direct co-products). Processing of these additional co-products was assumed to take place within the oil mill area so that no transportation was needed for the EFB feedstock. In the case of mulch, fresh EFB was directly transported to the plantation fields. The mulch, compost, and ethanol can be used internally or externally. Internal uses mean that the mulch or compost are applied to the plantation field to substitute inorganic fertilizer, or the ethanol is used as biofuel to substitute gasoline for the oil mill operation. External uses mean that these co-products will become part of another product, external to the palm oil, system.

The application of EFB as mulch or conversion of EFB into compost and ethanol were seen as a way to manage biomass residues leading to environmental improvement. Incineration was used to represent treatment of EFB in a waste processing unit. A controlled incineration was chosen since open burning is prohibited in a palm oil system. EFB can also be regarded as a direct co-product when it has market values. These different treatment and valuation of EFB are given in Table 1.

The models were developed with the LCA software CMLCA v5.2 (2012) based on inventories of Ecoinvent database v2.2 (2010). Impact indicator on global warming was chosen as the main criterion to compare LCA results. The impact assessment referred to CML 2001 method for climate change (GWP 100 year average, global).

Table 1: Guidelines on methodological choices for comparison of scenarios in terms of different treatment options and valuation of EFB

Scenario	System boundary of different treatment options with reference to the main palm oil system	EFB valuation	Approaches in dealing with multi-functional issues		
			Expanding the product system with additional co-products related to EFB	Partitioning of multi-functional processes	Substituting with avoided processes
0	Direct application of fresh EFB as mulch, internal or external uses*)	Wastes Goods	Mulch	Production of mulch	Production of inorganic fertilizer
1	Conversion of EFB to compost, internal use	Wastes	Compost	-	Production of inorganic fertilizer
2	Conversion of EFB to compost, external use	Wastes	Compost	Production of compost	-
3	Conversion of EFB to compost, internal use	Goods	Compost	-	Production of inorganic fertilizer
4	Conversion of EFB to compost, external use	Goods	Compost	-	-
5	Conversion of EFB to ethanol, internal use	Wastes	Ethanol	-	Production of gasoline
6	Conversion of EFB to ethanol, external use	Wastes	Ethanol	Production of ethanol	-
7	Conversion of EFB to ethanol, internal use	Goods	Ethanol	-	Production of gasoline
8	Conversion of EFB to ethanol, external use	Goods	Ethanol	-	-
9	Treatment of EFB in an incinerator, internal treatment	Wastes	-	-	-
10	Co-production (EFB is direct co-products), external use	Goods	-	Production of CPO, PKO, PKC, and EFB**)	-

*) The effect of the preparation of EFB as mulch on field sites (apart from transportation from oil mills to plantation fields) was so small that it did not change the base line value (see detail in Table 2). Therefore, it does not make any different either EFB was valued as wastes or goods, or either used internally or externally. For convenient, therefore, all of these variations are combined as one scenario.
**) CPO = Crude Palm Oil, PKO = Palm Kernel Oil, PKC = Palm Kernel Cake

The baseline of this comparison study is the production of CPO, PKO, and PKC without considering EFB processes in the inventory. Consequently, comparison among scenarios is carried out based on the multi-functional unit, CPO+PKO+PKC. The reason to choose these three products as a basis for comparison rather than mono-functional unit (CPO) is to better represent the total burden of the overall palm oil system. In Scenarios

0-8 and 10, the inclusion of EFB processes in the inventory resulted in additional co-products, i.e. mulch, compost, ethanol, and EFB. Meanwhile, Scenario 9 is only a waste treatment case with no multi-functional issues. When additional co-products from the EFB processes were introduced, the product system expanded from initially CPO+PKO+PKC into CPO+PKO+PKC+mulch, CPO+PKO+PKC+compost, CPO+PKO+PKC+ethanol, or CPO+PKO+PKC+EFB.

Table 1 summarizes guidelines on the methodological choices to assess environmental impact for the eleven scenarios reflecting different decision situations. The approaches used to solve multi-functional problems are a combination of system expansion, substitution, and partitioning depending on the nature of the scenario. For example, Scenarios 0-8 use a combination of system expansion and substitution, or system expansion and partitioning approaches. These Scenarios are expanded systems since they included additional co-products (mulch, compost, or ethanol). Scenario 10 uses only one method to solve multi-functional problems, i.e. partitioning. Substitution refers to the use of the resulted co-products within the main palm oil system (Scenarios 0, 1, 3, 5, and 7) with consequences of avoiding the use of other products of similar functions. In this regard, inorganic fertilizer and gasoline were chosen to substitute the mulch or compost, and the ethanol, respectively.

In addition to producing mulch, compost and ethanol, Scenarios 0, 2, and 6 were also recycling cases since the input EFB was valued as wastes. In this case, the environmental burden has to be partitioned between the upstream and downstream flows. This partitioning reflects burden attribution between the function to reduce the pollution strength of the waste (treatment) and the function to make new products (production).

Scenario 10 is a co-production case with EFB as a direct co-product having certain market values. In this regard, EFB as a co-product is sold to external parties, in which we do not have any control on their final uses. It could be used for example for compost, fibers, or energy.

Ecoinvent assumes that, in the palm oil system, the trunks, fiber, and shell are internally (closed-loop) recycled (Jungbluth et al, 2007). Here, the biomass residues in the plantation (trunks) were recycled with no significant additional inputs or net emissions. Fronds cut down along harvesting of FFB were not mentioned in the report, but we assumed that, together with the trunks, they were also recycled. Meanwhile, fiber, shell, and EFB were co-generated to produce energy for internally used in the oil mills. Our current study assumed the same, but excluded the EFB from the co-generation process and further treated it in various different ways.

The following section describes inventories of the main palm oil system and additional EFB processes in more detail. All processes were described by indicating the ID-number, region, and year of the Ecoinvent database. Also, assumptions used in every process are declared so that confirmation on the final LCA results could be made. Some modification from the default inventories was made, particularly for EFB availability (initially co-generated to produce energy), ethanol processes (feedstock transport), and incineration processes (additional prior drying).

1. Palm oil

The LCI model consisted of the production of FFB at farm (ID#199: Malaysia, 2002-2006) and palm oil in oil mills (ID#150MO: Malaysia, 1995-2006). The first inventory assumed that land provision included conversion of tropical rain forest to agricultural area with an emission value of 59 tonnes CO_2/ha. Plantation operation included field emissions of palm cultivation at 0.0945 kg CO_2/kg FFB, and farm-field transportation of seedlings and FFB at an average distance of 25 km, pesticides and fertilizers for further distance, 715 km.

The second inventory included 100 km transport of FFB from farm gates to oil mills and oil production. The oil production was based on mechanical processes, including oil extraction by screw press and removal of impurities (non-oil solids and liquid) by settling tank, centrifuge, and evaporator. Every kg of processed FFB resulted in 0.2156 kg CPO, 0.0266 kg PKO, and 0.0317 PKC. Economic values of these products were CPO= RM 1.490/kg, PKO= RM 2.565/kg, and PKC= RM 0.175/kg, in which RM (Ringgit Malaysia) is a Malaysian currency. Based on these data, economic partitioning coefficients were determined, CPO=81.3%, PKO=17.3%, PKC=1.4%. The treatment of POME was included in the inventory as an input service. Environmental performances of the palm oil system was based on multi-functional unit of 1000 kg CPO + 123 kg PKO + 147 kg PKC or 1270 kg CPO+PKO+PKC in short. In addition, the system also co-produced 1051 kg EFB at 40% dry matter.

All of the above data are based on Ecoinvent report No 17 (Jungbluth et al, 2010). A modification was made to the default inventory by excluding the contribution of EFB in energy production, a co-generation process (ID#79MO: Switzerland, 2000-2001).

2. Mulch

The LCI model consisted of the application of mulch (ID#171: Switzerland, 1991-2002). It is formulated as a service, not process. Production of inorganic fertilizers such as ammonium nitrate as N (ID#40<006484-52-2>: Europe, 1999), single superphosphate as P_2O_5 (ID# 54: Europe, 1999), and potassium chloride as K_2O (ID#50<007447-40-7>: Europe, 2000) were also included to account for the effect of mulch substitution with inorganic fertilizers, products of equivalent fertilizing values (Nemecek & Kägi, 2007). Transportation of mulch from oil mills to plantation fields adopted lorry transport (ID#1941: Europe, 2005) and tractor transport (ID#188: Switzerland, 1991-2002). Inorganic fertilizers which are less bulky than mulch were provided using additional rail transport (ID#1983: Europe, 2005). The transportation distances was based on 100 km between oil mills and farm gates (lorry) and 25 km between farm gates and plantation fields (tractor) for mulch, and additional 600 km of rail transport for substituted fertilizers (Jungbluth et al, 2010).

In the inventory, 1051 kg fresh EFB was directly applied as mulch. Land application as mulch would require approximately 30 ton EFB per hectare (Haron, 2013). Therefore, the economic outputs of the expanded system were 1270 kg CPO+PKO+PKC+ 0.035 ha of plantation area.

The fertilizing values of EFB mulch were adopted from Haron (2013), i.e. 0.8% N, 0.22% P_2O_5, and 2.9% K_2O fertilizer on dry basis. Similar values were also given by Caliman et al (2013). Based on the above unit processes, the mulch was equivalent to 9.61 kg ammonium nitrate, 4.40 kg superphosphate, and 20.32 kg potassium chloride. The production of the above amount of inorganic fertilizers emitted 103.9 kg CO_2-eq. The fertilizing value of the mulch is credited if it is internally used as fertilizer (Scenario 0). It means that internal utilization of 1051 kg or 0.035 ha EFB mulch will avoid global warming as much as 103.9 kg CO_2-eq.

3. Compost

The LCI model consisted of the production of compost (ID#58: Switzerland, 1999). It is formulated as a service, not process. The technology was based on open windrow composting as described in Ecoinvent report No 15 (Nemecek & Kägi, 2007). Unit processes for the production and transportation of inorganic fertilizers were the same as in the case of mulch. Chiew and Shimada (2013) suggested that 2600 kg of fresh EFB resulted in 1000 kg compost with fertilizing values of 2.2% N, 1.28% P, 2.79% K on dry basis.

In the inventory, 1051 kg EFB of 40% dry matter was converted to 404.2 kg compost of 50% dry matter. As a result, the economic outputs of the expanded system were 1270 kg CPO+PKO+PKC+ 404.2 kg compost. Based on the above unit processes, the compost was equivalent to 12.70 kg ammonium nitrate, 28.21 kg superphosphate, and 11.32 kg potassium chloride. The production of the above amount of inorganic fertilizers emitted 188.3 kg CO_2-eq. The fertilizing value of the compost is credited if it is internally used as fertilizer (Scenarios 1 and 3). It means that internal utilization of 404.2 kg EFB compost will avoid global warming as much as 188.3 kg CO_2-eq.

4. Ethanol

The LCI models consisted of the production of 95% ethanol by fermentation (ID#161MO: Switzerland, 1999-2006) and further distillation to 99.7% ethanol (ID#11795: Sweden, 2000-2008). The first inventory included the production of ethanol and electricity from hardwood chips. Process stages included pretreatment to isolate cellulose from wood matrix, simultaneous saccharification and co-fermentation, and distillation to recover ethanol. Economic partitioning coefficients of the resulted ethanol and electricity were 99.7% and 0.3%, respectively. Further description can be found in Jungbluth et al (2010). A modification was made to the default inventory by excluding the transportation of feedstock from forest to distillery (ID#161MO: Switzerland, 1999-2006). Production of gasoline (ID#1570: Switzerland, 1980-2000) was considered to account for the effect of ethanol substitution.

In the inventory, 0.00232 m^3 hardwood chips containing 0.55448 kg dry mass was converted to 0.144 kg 99.7% ethanol. All inputs and emissions for 1 kg dry EFB were assumed equal to those for 1 kg dry hardwood chips. As a result, the economic outputs of the expanded system were 1270 kg CPO+PKO+PKC+ 109.3 kg ethanol.

Energy content of ethanol and gasoline is 31 MJ/kg and 46 MJ/kg, respectively (Chiew and Shimada, 2013) Therefore, 109.3 kg ethanol is equivalent to 73.66 kg gasoline. The production of this amount of gasoline emitted 50.1 kg CO_2-eq. The energy content of the bioethanol is credited if it is internally used as biofuel (Scenarios 5 and 7). It means that internal utilization of 109.3 kg ethanol will avoid the use of 73.66 kg gasoline with global warming impact as much as 50.1 kg CO_2-eq.

5. Incinerator

The LCI model consisted of controlled burning of wood in a municipal solid waste incinerator (D#2130: Switzerland, 1994-2000). It is formulated as a service, not process. The incinerator produced electricity and heat, but no burden allocation was assigned to these co-products. The solid residues generated from incineration were landfilled. Further description can be found in Ecoinvent report No 13 (Doka, 2003).

Ecoinvent assumed that fresh EFB contained 60% moisture. Before it can be fed into an incinerator, drying is needed to bring the water content down to 20%. The unit process used for this purpose was grass drying (ID#160: Switzerland, 1985-2002). With 1051 kg EFB input, two processes were involved, i.e. evaporation of 525.5 kg water and incineration of 525.5 kg EFB of 80% dry matter.

6. EFB as direct co-products

The free on board (FOB) prices of EFB at the oil mills ranged between IDR 20/kg EFB and IDR 50/kg EFB, but often it was available for free (Anonymous field survey in Northern Sumatera, July 2011). The FOB price of palm oil at oil mills was IDR 9000/kg CPO (GAPKI, 2013). IDR (Indonesian Rupiah) is the Indonesian currency. These data were used to determine partial environmental burden charged to EFB as a direct co-product.

RESULTS AND DISCUSSION

Environmental performances of the palm oil system were based on the multi-functional unit of 1270 kg CPO+PKO+PKC. The global warming performance at the cradle-to-gate boundary (the plantation and oil mill phases) was 2068 kg CO_2-eq and at the gate-to-gate boundary (the oil mill phase) was 144.7 kg CO_2-eq. These results were based on the Ecoinvent assumption that in the oil mills, EFB together with shell and fiber were burned in a co-generation process to produce heat and electricity for mill operation. In the current paper, we assumed that EFB was available for various other treatments while the energy produced by fiber and shell were sufficient to supply energy need of the whole mill operation. In fact, this is often the case in practice. Therefore, we made adjustment by excluding the EFB contribution to the co-generation process, which was found to be 20.8 kg CO_2-eq. Subtracting this to the default values, the global warming performances of the cradle-to-gate system and gate-to-gate system changes to 2047 kg CO_2-eq and 123.9 kg CO_2-eq, respectively. Contribution of the upstream operations up to the farm gate amounted 94% of the total CO_2-eq emissions. Transport of FFB from the farm gate to the oil mill and its operations hence only accounted for the remaining 6% or 123.9 kg CO_2-eq/1270 kg CPO+PKO+PKC.

Along the whole chain, the contribution of the provision of land and plantation operations was so dominant that the effects of different treatment on EFB on final LCA results could hardly be observed at the cradle-to-gate boundary. Therefore, the process of producing FFB in the plantation was cut off. It means that the performances of the upstream and downstream processes to the oil mills were assumed constant. This assumption is needed to justify that the comparison was made at the gate-to-gate boundary. Therefore, we further looked at changes due to different treatments on EFB only within the oil mill boundary.

The implementation of the proposed guidelines on methodological choices to compare eleven possible scenarios is presented in Table 2. It illustrates a step-by-step calculation of the final results. In this context, the global warming impacts were adjusted considering multi-functional problems in terms of expanding the product system with additional co-products, substitution with equivalent products, or burden partitioning. These guidelines accommodate the facts that the presence of additional co-products had consequences to other product systems. An example for this mechanism is substitution of mulch, compost, or ethanol with equivalent products such as inorganic fertilizer or fossil fuel, respectively.

Based on the last two columns in Table 2, the global warming impacts of the eleven scenarios are visualized in Figure 2. Comparison is based on how products of the EFB processes are used with reference to the palm oil system: internal uses (Scenarios 0, 1, 3, 5, 7, and 9) or external uses (Scenarios 2, 4, 6, 8, and 10). The last column in Table 2 or the white bars in Figure 2 represent the impact of the additional co-products (mulch, compost, ethanol, or EFB) when used externally. Next to the last column in Table 2 or black bars in Figure 2 represent the final impacts of the main palm oil products (CPO+PKO+PKC).

Comparison based on the same multi-functional units CPO+PKO+PKC is possible only for Scenarios 0, 1, 3, 5, 7, and 9. These first five scenarios were solved with a combination of system expansion, substitution, and partitioning approaches, while the last scenario is a simple waste treatment case with no multi-functional problem. It is assumed that the fertilizer processes were the avoided processes, producing co-products of equivalent function as mulch or compost. The gasoline processes were the avoided processes, producing co-products of equivalent function as ethanol. Therefore, the functional units of these scenarios after the inclusion of co-products and substitution with equivalent products are:

- Scenarios 0: (CPO+PKO+PKC) + (mulch) - (fertilizer) ≈ (CPO+PKO+PKC)’

•Scenarios 1 and 3: (CPO+PKO+PKC) + (compost) - (fertilizer) ≈ (CPO+PKO+PKC)’’

•Scenarios 5 and 7: (CPO+PKO+PKC) + (ethanol) - (gasoline) ≈ (CPO+PKO+PKC)’’’

•Scenario 9: (CPO+PKO+PKC) ≈ (CPO+PKO+PKC)’’’’.

These multi-functional flows (CPO+PKO+PKC), (CPO+PKO+PKC)’, (CPO+PKO+PKC)’’, (CPO+PKO+PKC)’’’, and (CPO+PKO+PKC)’’’’ have different emission values that can be used as a basis for comparison. Further, this comparison is valid since they have the same functional unit (CPO+PKO+PKC) and unit (kg CO_2-eq).

Table 2: Global warming performances of a palm oil system reckoning with different treatment options and valuation of EFB (kg CO_2-eq/1270 kg CPO+PKO+PKC)

Scenario	System boundary of different treatment options with reference to the main palm oil system	Initial value	Adjustment on LCA scores considering multi-functional issues			Final value	
		CPO + PKO + PKC *)	Expanding the product system with additional co-products	Partitioning of multi-functional processes	Substituting with avoided processes**)	CPO + PKO + PKC	Mulch, compost, ethanol, EFB for external uses
0 M	Wastes or Goods, Mulch, Internal or External***)	123.9	0.7	negligible	−103.9	20.7	negligible
1 WCI	Wastes, Compost, Internal	123.9	+146.4	·	−188.3	82.0	·
2a WCE	Wastes, Compost, External (treatment:prod.=2:1)	123.9	·	+97.6****)	·	221.5	48.8****)
2b WCE	Wastes, Compost, External (treatment:prod.=1:2)	123.9	·	+48.8****)	·	172.7	97.6****)
3 GCI	Goods, Compost, Internal	123.9	+146.4	·	−188.3	82.0	·
4 GCE	Goods, Compost, External	123.9	·	·	·	123.9	146.4
5 WEI	Wastes, Ethanol, Internal	123.9	+42.2*****)	·	−50.1	116.0	·
6a WEE	Wastes, Ethanol, External (treatment:prod.=2:1)	123.9	·	+28.1****)	·	152.0	14.1****)
6b WEE	Wastes, Ethanol, External (treatment:prod.=1:2)	123.9	·	+14.1****)	·	138.0	28.1****)
7 GEI	Goods, Ethanol, Internal	123.9	+42.2*****)	·	−50.1	116.0	·
8 GEE	Goods, Ethanol, External	123.9	·	·	·	123.9	42.2*****)
9******) WI	Wastes, Incinerator	123.9	·	·	·	366.8	·
10a Gcop	Goods, co-Production EFB price = 0.0022*CPO	123.9	·	−0.3	·	123.6	0.3
10b Gcop	Goods, co-Production EFB price = 0.0056*CPO	123.9	·	−0.8	·	123.1	0.8

*) Corrected values, i.e. 144.7 (default) – 20.8 (EFB contribution in co-generation process) = 123.9 kg CO_2-eq.

**) Substitution with NPK fertilizer (9.61 kg ammonium nitrate + 4.40 kg superphosphate + 20.32 kg potassium chloride = 1051 kg or 0.035 ha of EFB mulch), (12.70 kg ammonium nitrate + 28.21 kg superphosphate + 11.32 kg potassium chloride = 404.2 kg of EFB compost), or with fossil fuel (73.66 kg gasoline = 109.3 kg 99.7% ethanol).

***) The effect of the application of EFB as mulch was so small (0.7 kg CO_2-eq) that it practically became negligible when partitioned.

****) Partitioning ratio of 2:1 indicates that Scenarios 2a and 6a allocated twice heavier burden for reducing the pollution strength of EFB than for producing compost or ethanol. In contrast, Scenarios 2b and 6b (1:2) allocated twice heavier burden for producing compost or ethanol than reducing the pollution strength of EFB.
*****) Corrected values, i.e. 57.1 (default) – 14.9 (transportation of wood chips from forest to distillery) = 42.2 kg CO_2-eq.
******) Consisted of two processes: drying (237.1 kg CO_2-eq) and incineration (6.2 kg CO_2-eq).

The results presented in Figure 2 are point value data with no uncertainty estimates. LCA results are compared based on these point values since additional assumptions and data, other than those from Ecoinvent, were not completed with uncertainty estimates. However, these data are sufficient to illustrate how comparison among different scenarios was done.

Comparison of LCA results among scenarios was based on the same functional units with reference to the specific objective of the study. In the current paper, such comparison can be performed only for Scenarios 0, 1, 3, 5, 7, and 9 in which the multi-functional units CPO+PKO+PKC is represented as black bars in Figure 2. These first five scenarios are the cases where the mulch, compost, and ethanol were used internally to substitute inorganic fertilizers and gasoline, respectively. The comparison was based on global warming impact of a reference case with an initial value of 123.9 kg CO_2-eq/1270 kg CPO+PKO+PKC (dashed line in Figure 2). In this reference case, EFB treatments were not included in the process inventory. The results indicate that, based on global warming impact of producing 1270 kg CPO+PKO+PKC, the mulch option (20.7 kg CO_2-eq) was the best choice as compared to compost (82.0 kg CO_2-eq), ethanol (116.0 kg CO_2-eq), or incineration (366.8 kg CO_2-eq) options.

Incorporation of transportation of processed EFB (125 km) and the avoided substituted fertilizers (725 km) increased the impact by 33.2 kg CO_2-eq for the mulch option and 10.6 kg CO_2-eq for the compost option. These transportation related burdens in Figure 2 are presented as dashed boxes placed on top of the black boxes. The effect of the avoided process of producing substituted fertilizers was more dominant in determining final results (103.9 kg CO_2-eq and 188.3 kg CO_2-eq for mulch and compost, respectively). A sensitivity analysis for different process of substituted fertilizers and transport distances seems necessary in these kinds of closed-loop applications. Such analysis however was not included in the current study to avoid further complication.

The process of producing compost (146.4 kg CO_2-eq) gave higher impact than producing ethanol (42.2 kg CO_2-eq). The reason is related to the choice on using open-windrow process which emitted GHG from composting piles directly to the atmosphere. However, this high burden process of producing compost was compensated by the avoided process of producing substituted fertilizers. As a result, the overall performance of the compost was better than the ethanol options. The incineration scenario was the worst case because fresh EFB contained large amount (60%) of moisture. Before the EFB can be fed into an incinerator, drying is needed to evaporate the water to only 20%. This drying step was found to be the major contributor (237.1 kg CO_2-eq) to the incineration option. In this closed-loop system, the status of EFB as wastes or goods had no effect on final results (Scenario 0 for mulch, Scenarios 1 and 3 for compost, and Scenarios 5 and 7 for ethanol).

In practice, there are other influential factors on the management of EFB. For example, a company that we visited in Sumatera informed that when applying EFB on commercial plantation fields, the total distance is usually within 10 km. This criterion to limit transport distances for EFB field application was mostly based on economic consideration rather than environmental assessment. However, this could also serve as basis for the company to define which portion of EFB may be available for ethanol conversion by comparing the co-product scenarios with varying distances.

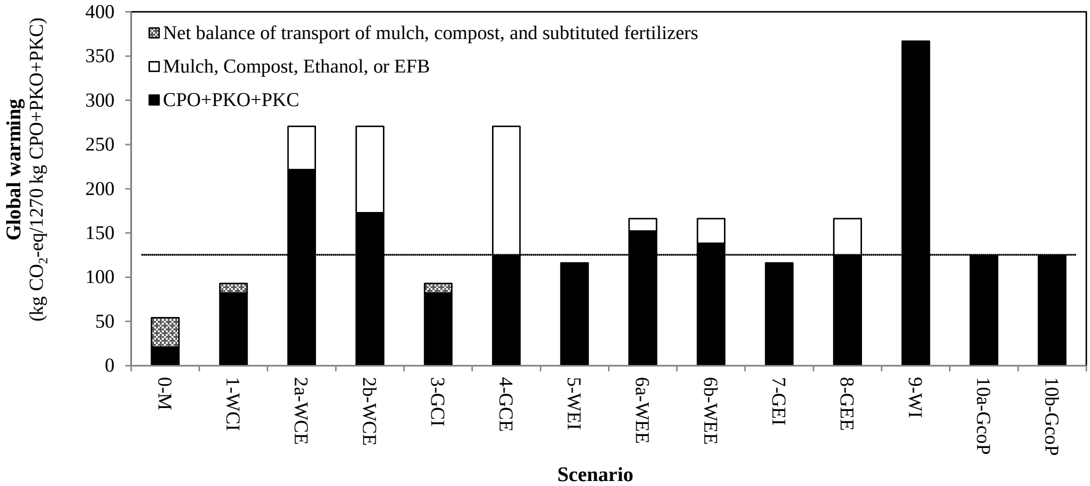

Figure 2: Global warming performances of different scenarios. Dashed line is the reference case (EFB treatments were not included in the inventory) with an impact score of 123.9 kg CO_2-eq/1270 kg CPO+PKO+PKC.

Comparison of LCA results cannot be made for Scenarios 2, 4, 6, 8, and 10. The expanded functional units of these scenarios are CPO+PKO+PKC+additional co-products (compost, ethanol, or EFB). These co-products in Figure 2 are represented as white bars. They are used externally, and we do not have any knowledge on their specific utilization by other parties. Therefore, substitution mechanism as in the case of internal uses could not be performed. Instead, these co-products with their embedded emissions entered other product systems, external to palm oil systems. Selling the EFB as co-products to an external ethanol plant or converting the EFB internally, for example, would give the same impact provided that the same technology is used.

The status of EFB as wastes strongly influences the final LCA results. These are the cases of Scenarios 2a, 2b, 6a, and 6b in which the environmental burden was split between the upstream link and downstream links. Partitioning also applied for the co-production cases (Scenarios 10a and 10b), but the effect of EFB as co-products was so small that it cannot be seen in Figure 2. This is because the values of EFB were much lower than the prices of the main palm oil products (CPO, PKO, and PKC). If the price of EFB increases, the effect of this co-product to the palm oil system will increase accordingly.

The above comparative analysis was by no means complete. It for example did not include transportation of ethanol from distillery to gas station and its emissions on use. Also, the plantation phase might use fertilizers provided through import with longer transport distances. The mulch or compost was introduced through substitution of the fertilizing values of the mineral equivalent. This is quite simplistic approach since it did not consider for example the difference in N-emissions between organic and mineral fertilizers, the role of organic fertilizers on soil structure, biodiversity, and long-term soil fertility. The mineral fertilizer equivalent, however, may be the only easily implementable approach available at this moment.

In the context of time and location, the palm oil inventory represents Malaysian average for 2002-2006, while the EFB processes were mostly European cases, particularly Switzerland. Further studies using a more specific system definition would reduce some uncertainty and better illustrate the usefulness of the proposed guidelines. However, we think that the analysis is sufficient to illustrate how comparison among different scenarios was done.

CONCLUSIONS

Comparison among LCA results based on the same multi-functional units can be done only in the cases where additional co-products were used internally. In this closed-loop system, the status of EFB as wastes or goods has no effect on final results. Based on global warming impact, the mulch option was the best choice as compared to the compost, ethanol, or incineration options. The effect of the avoided process of producing substituted fertilizers was dominant in this comparison result.

If used externally, the co-products with known burden characteristics will become part of another product, external to the palm oil, system. The status of EFB as wastes strongly influences final LCA results due to burden partitioning between the function to reduce the pollution strength of wastes and function to make products. Comparison with other scenarios requires further analysis incorporating specific uses of these co-products by external parties.

The proposed guidelines provide methodological choices in terms of system boundary, functional unit, and solution to multi-functional problems. The methods can be used to systematically compare LCA results of different treatment options and valuation of EFB in a palm oil system. The best alternative in handling biomass residues could improve environmental performances of the system and orient towards best practices, such as those suggested by RSPO. Further studies using a specific case of palm oil systems would better illustrate the usefulness of the proposed guidelines. Although the approach was illustrated for a palm oil system, it is also readily applicable for handling biomass residues in other agro-based industrial systems.

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