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ORIGINAL ARTICLE

Greenhouse gas assessment of palm oil mill biorefinery in Thailand from a life cycle perspective

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Abstract The purpose of this study is to provide a comprehensive assessment of oil palm biomass waste utilization, with the goal of providing palm oil mill owners the best options for biomass applications in order to limit carbon emissions and optimize economic potential. As the third largest producer of palm oil in the world, Thailand is very entrenched in the industry and thus is an ideal country to implement waste utilization strategies. The biomass byproducts result from the processing of fresh fruit bunches (FFB) from the oil palm plant in order to extract the main commodity, crude palm oil (CPO). This paper assesses six major biomass byproducts that result from the processing of the oil palm plants: empty fruit bunches (EFB), palm kernel shells (PKS), mesocarp fiber, oil palm fronds, oil palm trunks, and palm oil mill effluent (POME). The associated net greenhouse gas emissions were calculated for each biomass' potential utilization pathway. The results of the study found that 4 of the 6 biomass waste products have alternative utilization options that resulted in net negative carbon emissions. Regarding the utilization options that are recommended, EFB shows net emissions of −0.14 t CO_2 equivalent, −5.33 for shells, −17.68 for fiber, and −0.594 for trunks. In addition, the assessment of the added value for each product guides decision making to ensure economic viability. This analysis is unique in that it encompasses various utilization pathways for each of the major oil palm waste products in one comprehensive study. By comparing the results of these pathways, an optimal use for every waste product is recommended to decrease the overall climate change impact of the mill.

Keywords LCA · Palm oil biorefinery · Empty fruit bunches · Palm kernel shells · Oil palm trunk · Palm oil mill effluent

The original version of this article was revised: The last word in the title which was supposed to be "perspective" is missing. The correct title is shown above.

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1 Introduction

Southeast Asia is the most critical region for palm oil production as it is home to the three countries: Indonesia, Malaysia, and Thailand that together produce about 90% of the palm oil in the world [1]. Palm oil is extensively used in Southeast Asia and throughout the world for a variety of purposes including cooking, cosmetics, soaps, paints, and more recently the production of biodiesel. The demand for palm oil is increasing, and the United States Department of Agriculture (USDA) predicts that 65.39 million metric tons of palm oil will be produced worldwide in 2016–2017 [2].

In 2012, Thailand produced 10.94 million tons of fresh fruit bunches, making the country the third largest palm oil producer in the world [3]. Fresh fruit bunches (FFB) are processed to extract palm oil from the kernels, and this processing results in large amounts of waste biomass products such as the

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empty fruit bunches, palm kernel shells, mesocarp fiber, and wastewater known as palm oil mill effluent (POME). Other waste biomasses such as fronds and trunks come from the plantation rather than the palm oil mill. The overall oil palm industry is heavily criticized for deforestation throughout Southeast Asia and subsequent loss of biodiversity, decreased carbon sinks, and increased greenhouse gas emissions [4]. The palm oil industry is also vital to the economies of Southeast Asian countries, as historically these countries thrive in agricultural exports such as rice, rubber, and of course oil palm. Thus, sustainable utilization of palm oil mill waste is an attractive option to mitigate the negative impacts of the industry. Studies have been conducted in Indonesia and Malaysia attempting to address waste utilization, but none have given a holistic solution for the palm oil mill as presented in this study. One Malaysian study provided improvements to conventional practices regarding utilization of residues but did not recommend specific uses for each biomass [5].

This study uniquely assesses multiple utilization pathways for each waste biomass from trunks, fronds, and fresh fruit bunches (which yield the other biomasses). The makeup of biomasses coming from fresh fruit bunches is as follows: 20%–22% empty fruit bunches (EFB), 60%–65% wastewater (POME), 12%–14% mesocarp fiber, and 5%–6% palm kernel shell [3]. As previously mentioned, oil palm trunks and fronds are biomass waste from the plantation rather than the mill but will also be included in this study. The goal of this study is to evaluate how each of these currently underutilized biomasses could be better utilized in ways that mitigate greenhouse gas (GHG) emissions while still being economically feasible. Each biomass pathway was assessed across common or potential uses of that one biomass, and then the product pathway with the lowest net GHG emissions was suggested for that one biomass. Overall, this resulted in a holistic suggestion for the optimal use for each biomass involved in the mill and biorefinery processes. In addition to analyzing net GHG emissions, an economic review of each option was taken into consideration.

Empty fruit bunches are most commonly used as fertilizer at oil palm plantations or for mushroom cultivation due to their wet and bulky composition which makes them hard to transport and handle. They have a lignocellulosic composition which allows them to produce ethanol, but pretreatment is needed to break down the complex structure. There are average yearly quantities of around 2 million tons of EFB produced in Thailand, and there is potential to use this biomass for different forms of energy production [6]. The selling price of EFB is currently low, around 4.30 USD/t [7]. This study assessed the potential of EFB for use in combined heat and power plants (CHP), briquette production, and bioethanol production.

Palm kernel shells are a vital commodity due to their high calorific value and wood-like properties. Thailand produces about 720,000 t of shells every year [3]. Out of all the waste products, shells are sold for the highest profit by the palm oil mill. Therefore, they are not widely utilized in the mill besides their occasional use as a blend for fuel in boilers on site. This study assessed the global warming impacts associated with the use of shells in boilers for co-generation at the mill, as biochar for land application, as torrefied biocoal for 20% co-firing, as activated carbon, and as charcoal briquettes. Palm kernel shells' high calorific value and easy collection and transportation processes creates high demand globally for the waste product.

Oil palm mesocarp fiber, which is retrieved from fresh fruit bunches during the extraction of palm oil, is a versatile material that can be processed for various uses including compost fertilizer, animal feed, fiberboard, biocomposites, and CHP. Regarding CHP, potential emissions are significantly reduced when the fiber is integrated back into the palm oil mill for the steam and electricity generation [8]. Given its relatively high calorific value of around 20 MJ/kg, it was also advantageous to explore value-added products from fiber [9]. The products examined in this study include biomass feedstock, polypropylene biocomposites, and uncoated cellulosic fiberboard.

Oil palm fronds and trunks are waste from the plantation rather than the mill and are currently both utilized on site as fertilizer or mulch, providing nitrogen amongst other nutrients to the soil [7, 10]. Oil palm fronds are composed of lignin, hemicellulose, and cellulose (see Table A1, Appendix A in Supplementary material), and are a potential second-generation feedstock for bioethanol production [11]. Oil palm trunks are a non-wood material that has the potential as biofuel as well as in wood products such as plywood. Oil palm trunks have a relatively high moisture content (55-85%) compared to hard or soft woods which range between 40% and 60%; thus, the material is not suitable for replacing conventional structural material [12]. This study assessed fertilizer, animal feed, and ethanol pathways for fronds and fertilizer, biofuel, and plywood pathways for trunks.

The three processes that contribute to the production of wastewater are the sterilization of FFB, the clarification of crude palm oil, and the separation of the palm kernel from the shell. Characteristically, the wastewater has a high chemical oxygen demand (COD), biological oxygen demand (BOD), and high levels of total suspended solids including fats, oils, grease, as well as other organic material. For these reasons, the water must be treated before reuse or discharge. POME is commonly placed in open lagoons that produce highly fugitive methane emissions due to the lack of related environmental policies in most of Southeast Asia. Moving forward, in Thailand, there is an increased focus on closed digestion systems to collect biogas in order to reduce greenhouse gas emissions and take advantage of government policies that incentivize renewable electricity generation.

When making decisions regarding utilization of waste, greenhouse gas emissions as well as economics must be considered. As climate change becomes an increasingly apparent threat to society, Thailand has implemented many economic policies to promote alternative energy production. The Alternative Energy Development Plan (AEDP 2015-2036) aims to almost double biomass energy production by 2036 [13]. The palm oil industry will be instrumental in reaching this goal.

This study is unique in that it comprehensively assessed the climate change potential and economic added value for each waste product utilization pathway. This will provide palm oil mill operators with vital information to reduce their overall impact on climate change while optimizing the economic potential of the mill.

2 Materials and methods

2.1 Goal and scope definition

The goal of this study was to assess and recommend various pathways of oil palm biomass utilization based on climate change potential and economic considerations. The findings of this study may be used by plantation, mill, and biorefinery owners. Calculations regarding emissions from electricity generation used Thai grid mix data; thus, the results should be used only by countries with a grid mix comparable to that of Thailand. This study has potential to be applied in Malaysia and Indonesia as they have similar electricity grid mixes and biorefinery practices. GHG emissions for the processes assessed are highly dependent on current technologies available and thus this study can be considered valid for approximately 10 years. The functional unit is 50 t of FFB processed, from which the reference flows for each biomass were extrapolated, referenced in Table 1. Given the varying size of palm oil mills in Thailand, 50 t per hour was the average processing rate determined, thus modeling the study after an average size mill. Table 2 represents the amount of new products that yield from the reference flows of the respective waste products. These amounts were derived from 50 t of FFB and were used to calculate associated GHG emissions throughout the analysis [14]. This study primarily focused on GHG emissions as a method of assessing the impacts of a pathway on climate change.

Table 1 Functional unit and reference flows

Input	Quantity	Unit
FFB (wet)	50	tonne
Output		
EFB (wet)	10	tonne
Shells (wet)	2.75	tonne
Fiber (wet)	7	tonne
Fronds (wet)	19.01	tonne
Trunks (wet)	0.421	tonne
POME (wet)	25	m^3

Each pathway analysis began at the processing of the waste product itself and continued through its intended utilization seen in Fig. 1. Since the waste biomass generated was proportional to the amount of FFB input, the cultivation and processing stages were excluded from the scope; the emissions from cultivating oil palm were the same for each pathway. The disposal stage was excluded due to the focus of this study being on producing value-added products. When interpreting this data, it is important to note that the recommendations made to oil palm mills are based on global warming potential. Global warming potential enabled the clearest comparison between utilization options. This made the assessment of greenhouse gas emissions the most effective method in comparing a large number of pathways. Specific assessment of other implications besides greenhouse gas emissions associated with recommended pathways could further minimize the oil palm mill's environmental impact [15].

Figure 1 represents all of the possible pathways for each waste product (empty fruit bunches, palm kernel shells, fronds, trunks, mesocarp fiber, and POME). Each of the products will be assessed for GHG emissions associated with production. Figures 2, 3, 4, 5, 6, 7 outline the inputs and outputs of each production process as well as emphasize the stages in the processes which produce emissions. These diagrams are important in understanding the technologies and processes that lead to the final use of the new product. These new products perform functions that take the place of existing materials. When the old material is not needed anymore, the emissions from producing said material are avoided. For example, in Fig. 2, the production of bioethanol from empty fruit bunches replaces the need for gasoline. The avoided gasoline emissions are subtracted from the production emissions of bioethanol because bioethanol can now perform the function that gasoline typically would. The subtraction of avoided gasoline emissions from ethanol production emissions results in the net emissions used to make recommendations in this study.

2.2 Inventory analysis

Life cycle inventories were compiled for each utilization pathway that was explored and are referenced below and in Appendix B in Supplementary material. As shown in Table 1, the functional unit is 50 t of FFB processed, from which the reference flows were extrapolated. Table 3 clarifies

Table 2 Output reference flow for each pathway

Material	Pathways	Output product quantity	Unit
EFB	Briquette production	3.3	t briquettes
	CHP	4.3	MWh bioelectricity
Shells	Activated carbon	0.41	t activated carbon
	Biochar	0.95	t biochar
	Torrefied biocoal	1.02	t biocoal
	Charcoal briquette	1.32	t briquettes
	Biomass cogeneration	7514	MJ bioelectricity
Fiber	Torrefaction for biomass feedstock	5.26	t biomass feedstock
	Polypropylene biocomposite	5.60	t biocomposite
	Uncoated cellulosic fiberboard	7.37	t fiberboard
Fronds	Animal feed pellets	19	t bagged pellets
EFB and Fronds	Ethanol	D. Acid 3663 D. Alkali 3709 Hot water 3701 Steam explosion 3338	L EtOH
Trunks	Biofuel pellets	0.4	t bagged pellets
	Plywood	0.19	t plywood
	Fertilizer (fertilizer (trunks and fronds combined)	N 80 P_2O_5 30 K_2O 280	kg nutrient
POME	Modified covered lagoon (MCL)	25	m^3 wastewater
	Continuous stirred tank reactor (CSTR)	25	m^3 wastewater
	Up-flow anaerobic sludge fixed filter (UASFF)	25	m^3 wastewater
	Up-flow anaerobic sludge blanket (UASB)	25	m^3 wastewater

the individual assumptions for each pathway. All pathways used the emission factors associated with the current Thai grid mix. The ISO 14040 and ISO 14044 LCA methods enabled the analysis of greenhouse gas emissions from a life-cycle perspective. The ReCiPe methodology for Life Cycle Impact Assessment was used to assess the impacts on climate change by the 100-year hierarchist values to create carbon dioxide equivalents for each pathway. Table 3 contains all of the process assumptions and data used in order to make calculations for each individual pathway. The table can be referenced for detailed information on the processes and technologies analyzed. The supplementary materials provide a breakdown of the GHG emissions produced from the pathways assessed.

The bioethanol production process consists of pretreatment, hydrolysis of cellulose and hemicellulose, SSCoF (simultaneous saccharification and co-fermentation), and separation of lignin (co-product) and ethanol [16]. Of those sub-processes, this study focused on comparing four of the most common and feasible pretreatment options for lignocellulosic bioethanol production (dilute acid, dilute alkali, hot water, and steam explosion). This is outlined in Table 3.

Some biomasses that are currently being used for fertilizer (trunks, fronds, EFB) have the potential to be redirected to a new utilization pathway. This necessitates the production and application of replacement synthetic fertilizer which adds GHG emissions to the alternative pathway. For example, fronds are currently being used for fertilizer in Thailand, thus if they are to be redirected to another pathway (ethanol or animal feed) then production and application of a replacement synthetic fertilizer must be accounted for in the emission data of the redirected pathway (ethanol or animal feed). As per Table 3, the production of fertilizer nutrients (N, P_2O_5, and K_2O) is avoided or added to the redirected pathway in the amount that fronds and trunks provide N, P_2O_5, and K_2O. N_2O emissions were calculated based on the kilogram of nitrogen applied according to US EPA emission factors. This is further described in Appendix B12 in Supplementary material.

The greenhouse gas emissions from the wastewater treatment system were estimated using the method, AMS-III.H: methane recovery in wastewater treatment

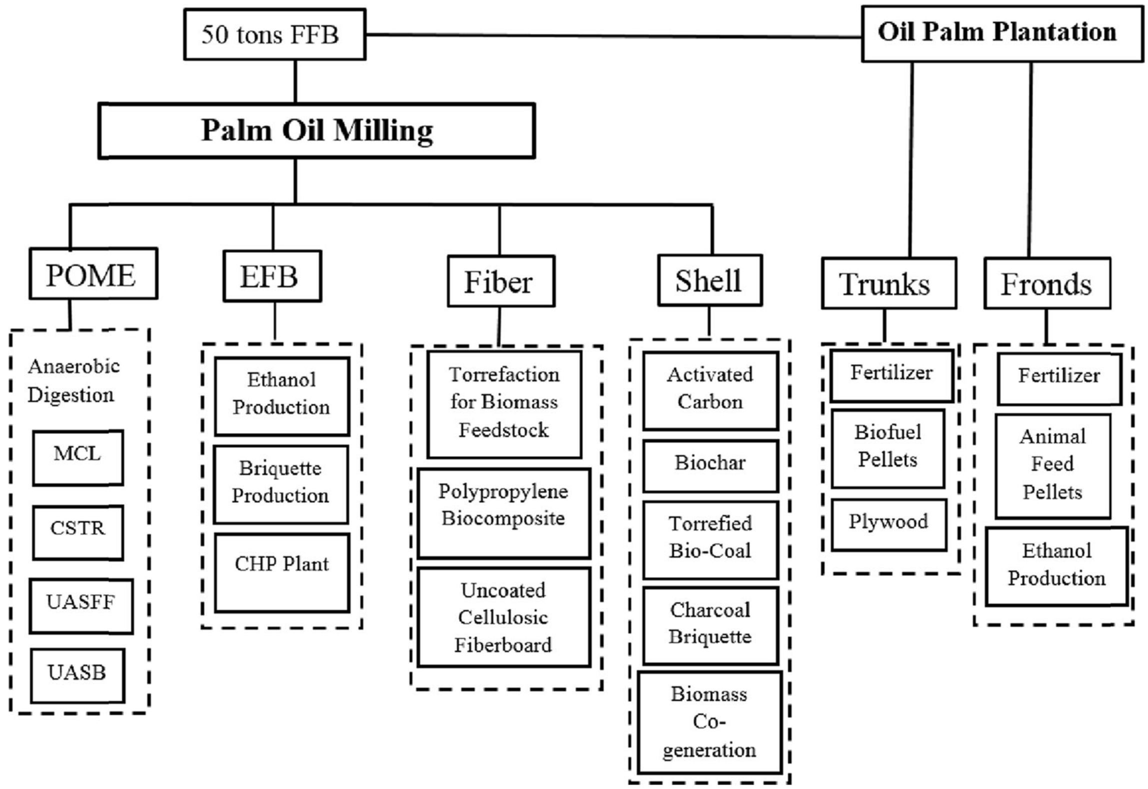


Fig. 1 Potential utilization pathways assessed for each biomass

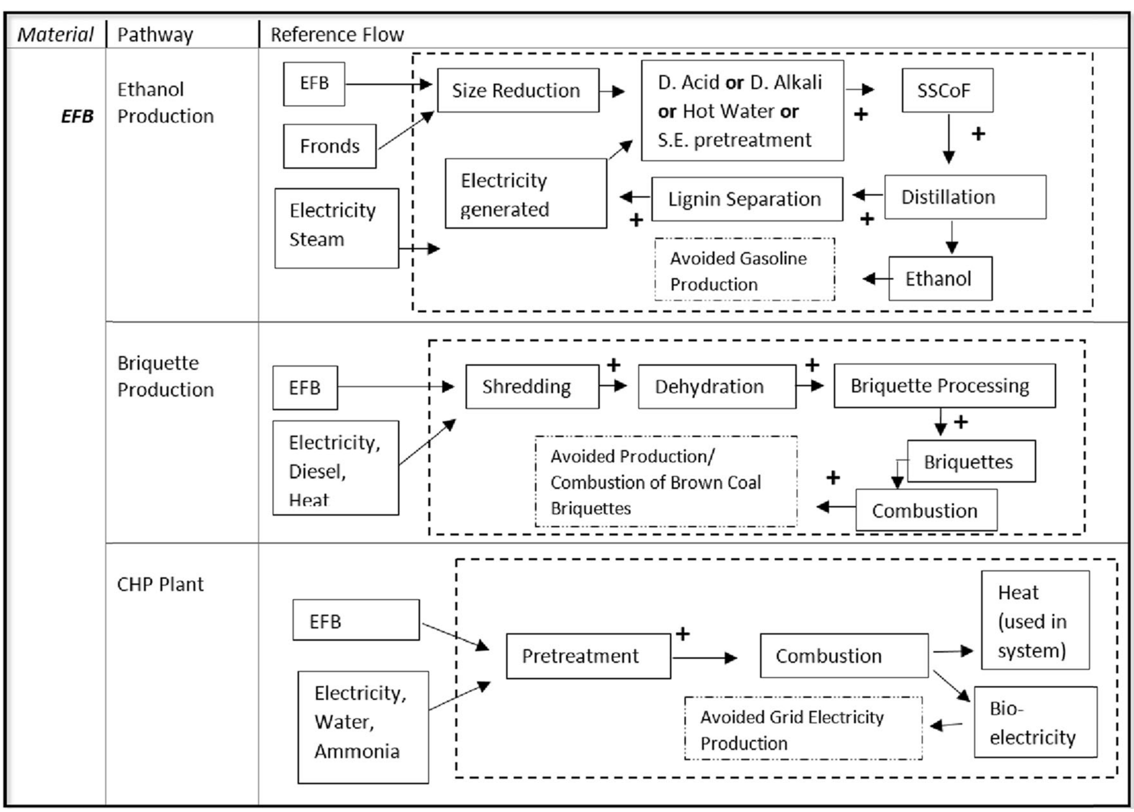


Fig. 2 System diagrams for EFB pathways; *plus sign* follows GHG producing processes; *dotted box* indicates system boundaries. Guidelines apply for Figs. 2, 3, 4, 5, 6, 7

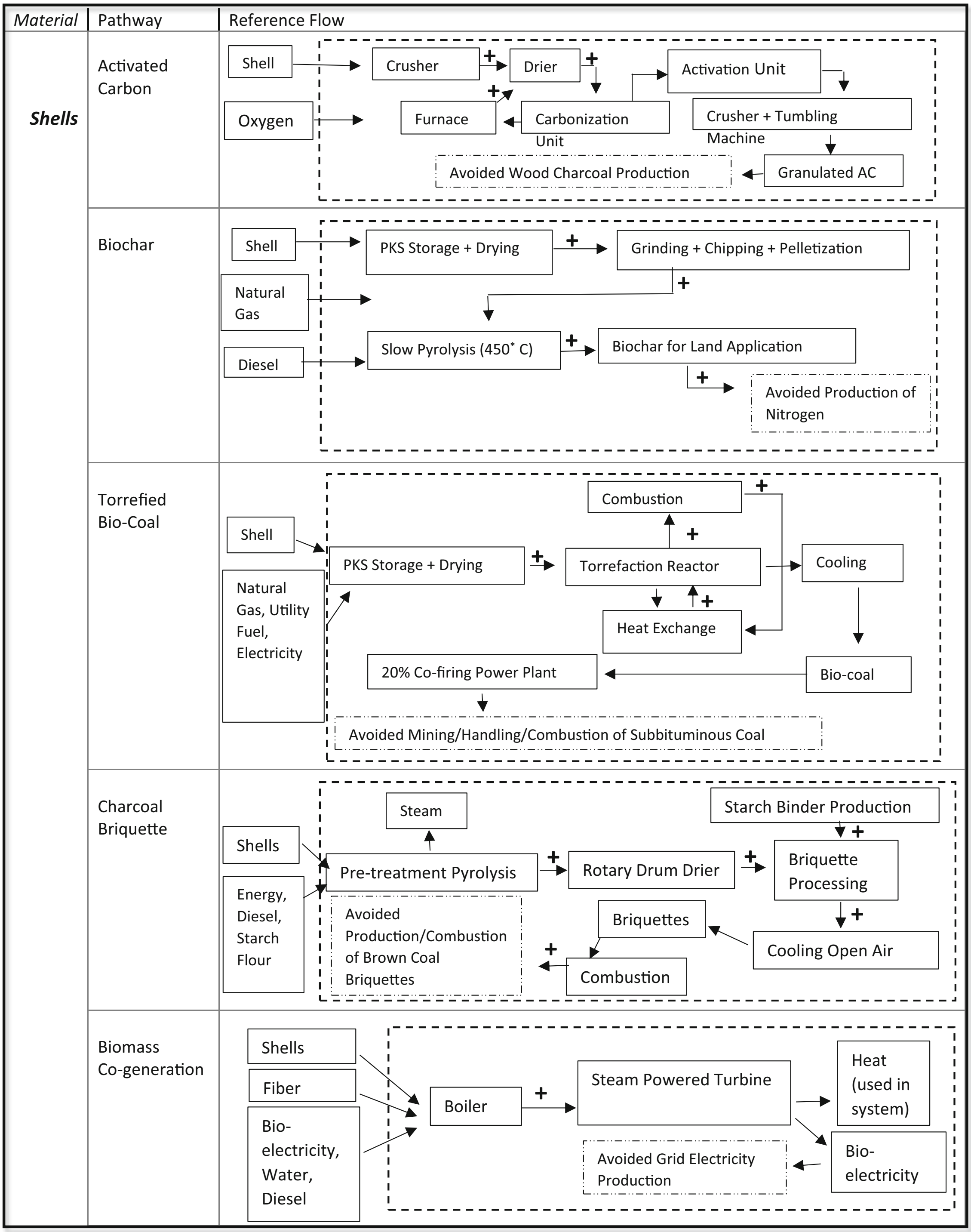


Fig. 3 System diagrams for shell pathways

[17]. This is a small-scale methodology developed by the United Nation's Clean Development Mechanism (CDM) that is particularly ideal for systems that use anaerobic digestion with biogas recovery technologies in their wastewater treatment systems [17]. The methodology uses the following factors: volume of wastewater (m^3/year), COD removed (t/m^3), methane-producing capacity, methane conversion factor, global warming potential, as well as the capture efficiency of the system to estimate emissions captured from the closed part of the system undergoing anaerobic digestion. For systems that utilize methane capture technologies, most emissions come from the subsequent post-treatment ponds, which further undergo digestion reducing the COD of the wastewater, thus generating emissions.

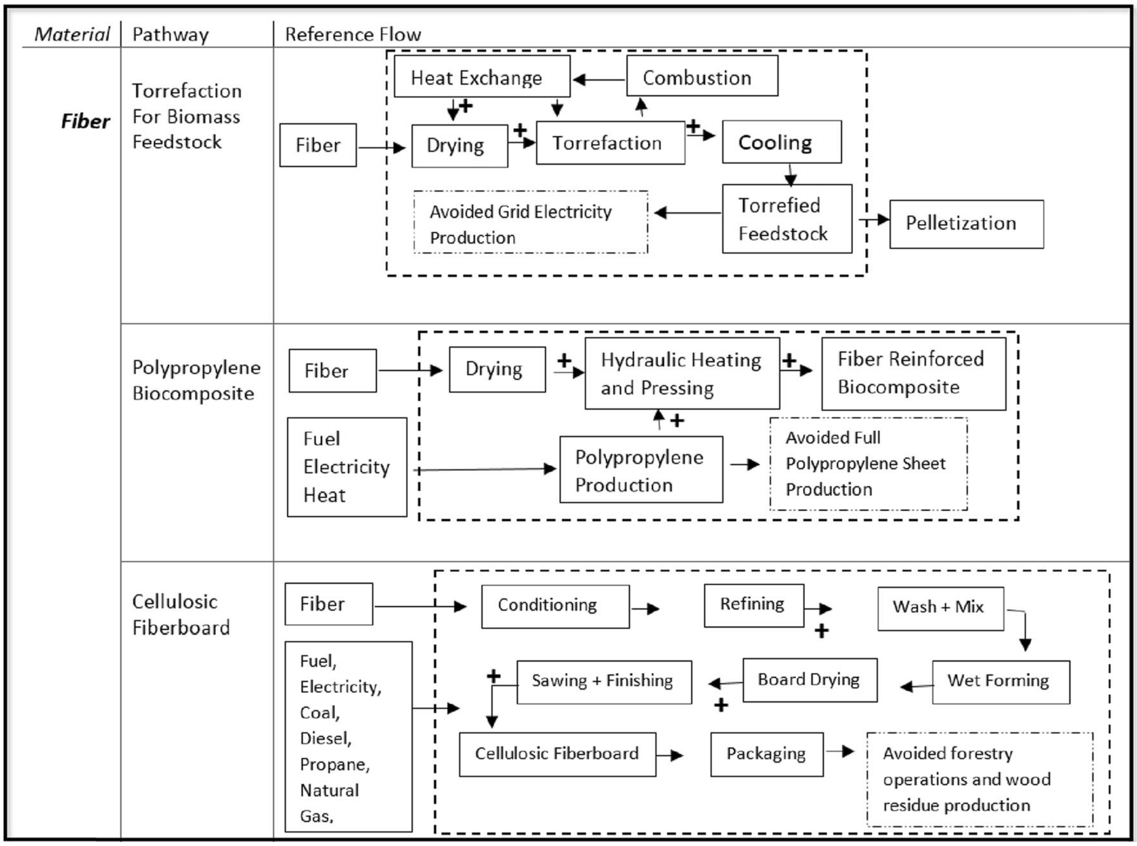


Fig. 4 System diagrams for fiber pathways

2.3 Global warming potential and value-added methodology

Figures 8, 9, 10, 11, 12, 13, 14 illustrate the net GHG emissions from each of the pathways defined in Table 3. Net emissions were calculated by subtracting the avoided emissions from the total emissions produced. All the pathways assessed were chosen based their viability as a new good produced from the biomass waste product. The current and past uses were taken into consideration to evaluate avoided emissions.

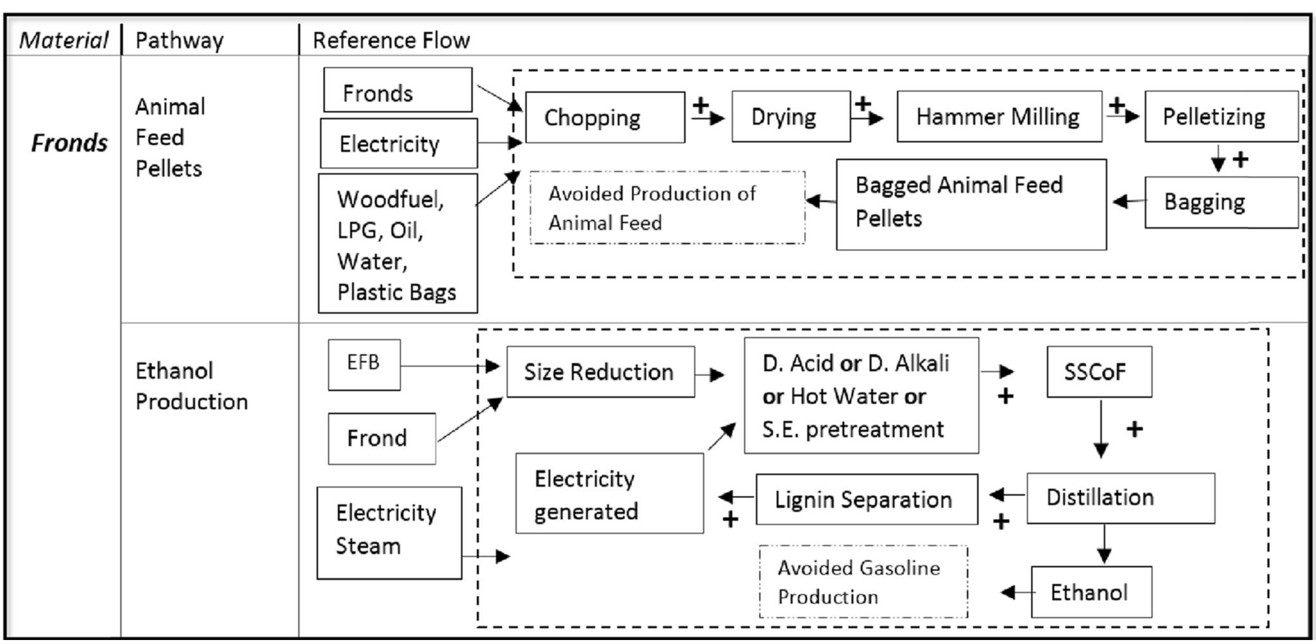


Fig. 5 System diagrams for frond pathways

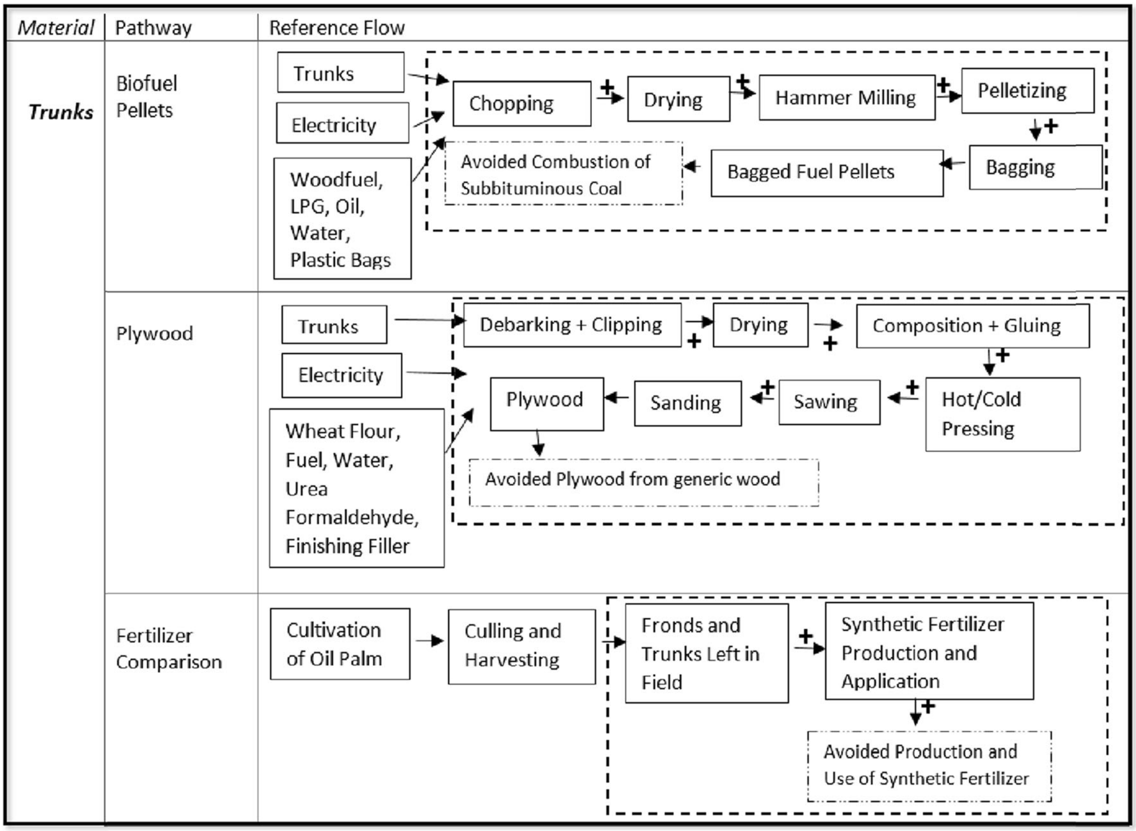


Fig. 6 System diagrams for trunk pathways

Figure 4 displays the added value for each of the pathways. These values were calculated by subtracting the market price of the product from the cost of producing that product, resulting in net added value. The value-added calculations were done using the reference flow output of products referenced in Table 2. Net GHG emissions were compared for different pathways within one biomass waste product. For example, the GHG emissions from using fronds for fertilizer and for animal feed were compared. However, GHG emissions from animal feed production were not compared to pathways of trunks, mesocarp fiber, EFB, etc. As previously stated, the specifics of replacing a redirected pathway are important. In order to make an overarching recommendation for a biorefinery or mill, an economic consideration is necessary. However, the environmental implications (net GHG emissions) took priority.

3 Results and discussion

3.1 Combined heat and power

EFB, shells, and fiber can be used for combined heat and power production. Electricity generated from these biomasses can be used to power palm oil mills or connect to the national

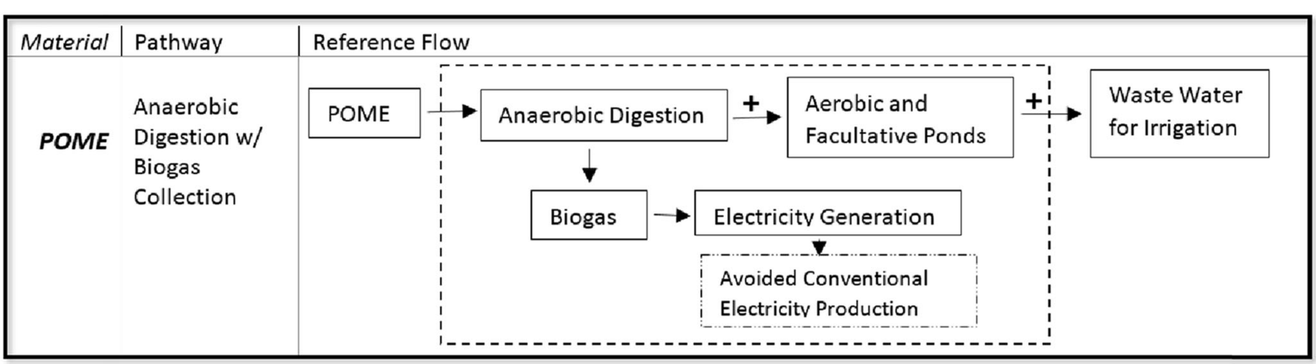


Fig. 7 System diagram for POME pathways

Table 3 Inventory analysis and data sources

Material	Pathway	Inventory analysis	Process and avoided emissions data sources
EFB	Ethanol production	Feedstock is a 1:1 ratio combining fronds and EFB, thus the reference flow is an average of the two values (14.5 t input). Assume lignocellulosic biomass can substitute for other similarly composed lignocellulosic biomass. Production and combustion of gasoline is avoided.	[16] [18] [19]
	Briquette production	Calorific value of EFB briquette is 18 MJ per kg. Emissions from production and combustion of brown coal briquettes are avoided.	[20] [21]
	CHP plant	Emissions from electricity production from the grid mix are avoided.	Thailand National Database
Shells	Activated carbon	Shells are assumed to behave similarly to coconut shells. Emissions from production of wood charcoal are avoided.	[22] [23]
	Biochar	Shells are assumed to have similar characteristics and behaviors as wood. Biochar is intended for land use and replaces Nitrogen needed on the oil palm plantation. Production and use of nitrogen are avoided.	[23] [24]
	Torrefied biocoal	The torrefaction process for shells is assumed to have similar emissions as the torrefaction process for wood. Biocoal is torrefied at 20% in a co-firing plant. Emissions from combustion of sub-bituminous coal in the plant are avoided.	[25] [26] [21]
	Charcoal briquette	Shells are assumed to have similar emissions as wood pellet production. It is assumed that 4% of the briquette is starch binder. Calorific value of briquette is 23 MJ per kg. Emissions from production and combustion of brown coal briquettes are avoided.	[27] [21]
	Biomass co-generation	Shell/fiber ratio is 1:4 in the boilers. The emissions are produced from the input of diesel to start up the boilers. Emissions from electricity produced from the grid mix are avoided.	[28] Thai National Database
Fiber	Torrefaction for biomass feedstock	Fiber is torrefied between 200 and 300 °C to yield biomass feedstock and is assumed to behave similarly to woody crop biomass. Emissions are avoided when using feedstock (20 MJ/kg) for fuel (such as being integrated back into refinery).	[29] [30]
	Polypropylene biocomposite	Polypropylene composites are reinforced with fiber (assume similar to wood) in a ratio of 2:1. Emissions from production of full polypropylene sheets are avoided.	[31] [32]
	Uncoated cellulosic fiberboard	Uncoated cellulosic fiberboard made from mesocarp fiber (assumed similar to woody residue). Emissions avoided from cultivation for wood residues and forestry operations.	[33]
Fronds	Animal feed pellets	The pelletizing process is assumed similar to wood pellet production, as stated in source. Conventional animal feed production is avoided.	[34] [35]
	Ethanol production	Feedstock is a 1:1 ratio combining fronds and EFB; thus, the reference flow is an average of the two values (14.5 t input). Assume lignocellulosic biomass can substitute for other similarly composed lignocellulosic biomass. Production and combustion of gasoline is avoided.	[16] [18] [19]
	Fertilizer	Production of fertilizer nutrients (N, P_2O_5, and K_2O) is avoided in the amount that fronds; and trunks provide N, P_2O_5, and K_2O. N_2O emissions were calculated based on the kilogram of N applied according to US EPA emission factors.	[36] [37] [38]
Trunks	Biofuel pellets	Combustion of pellets is biogenic. Combustion of sub-bituminous coal is avoided. HHV of trunks is calculated using an equation based on volatile matter and fixed carbon contents.	[21] [39]
	Plywood	Inventory taken from LCA of moisture resistant oil palm based plywood. Conventional wood-based plywood production is avoided using LCI of softwood plywood.	[12] [40]
	Fertilizer	Production of fertilizer nutrients (N, P_2O_5, and K_2O) is avoided in the amount that fronds and trunks provide N, P_2O_5, and K_2O. N_2O emissions were calculated based on the kilogram of N applied according to US EPA emission factors.	[36] [37] [38]
POME	Anaerobic digestion	Starting COD content was assumed to be 65,000 mg/L The assumed COD removal efficiency of each system is as follows: Modified covered lagoon (MCL) - 70% Continuous stirred tank reactor (CSTR) - 80% Up-flow anaerobic sludge fixed filter (UASFF) - 97% Up-flow anaerobic sludge blanket (UASB) - 98.4%	[41] [42] [43]
	Biogas collection and utilization	Each treatment system was assumed to be equipped with a biogas collection system with a 90% capture efficiency.	[17] [44] [13]

Table 3 (continued)

Material	Pathway	Inventory analysis	Process and avoided emissions data sources
		All biogas produced was assumed to be burned in a gas engine generator with an engine conversion factor of 2.08 kWh/ m^3 of biogas. This is the chosen utilization option because of the feed-in-tariff option offered from the Thai government.	
	Aerobic and facultative ponds	After anaerobic digestion, the wastewater requires further treatment by aerobic and facultative processes in order to achieve a total COD removal efficiency of 99.9%.	[44]
	Wastewater and sludge	The wastewater will be utilized for irrigation purposes in nearby plantations, not discharged into waterways.	[7] [44]
		The sludge in the anaerobic digestion system will be monitored and removed when necessary. The sludge can be dried and used as fertilizer in local plantations, but emissions from avoiding chemical fertilizer production were not considered because sludge is only removed based on the need of the digestion system.	

grid. Figures 8 and 9 show negative GHG emissions for CHP production from EFB input as well as from the shell-fiber blend input, which is largely due to national grid electricity displacement. EFB briquettes also show highly negative GHG emissions, making this an appealing pathway for the biomass. However, as seen in Table 4, shells would be a better primary feedstock for briquette production, as the associated emissions are also low and the economic value of palm kernel shell briquettes is significantly higher than those made from EFB. The recommended utilization pathway for EFB is combined heat and power production. Shown in Table 4, there are negative associated GHG emissions and a value-added of 80 USD/10 t of input. If a palm oil mill's energy needs can be met by CHP, any excess empty fruit bunches may be briquetted and sold for profit.

3.2 Briquetting and pelletization

EFB, trunks, fiber, and shells all have the potential to be pelletized for a variety of energy uses. If EFB and fiber were primarily being used to provide power to the mill, shells, trunks, and fronds are available for pelletizing or producing biocoal. Figure 11 indicates that fronds have the lowest climate change potential when used as fertilizer in the plantation. Figures 9 and 12 display high negative values for climate change for both pelletized trunks and shell briquettes. In terms of climate change potential, fronds are best used as fertilizer while trunks and shells are better used as energy sources. The waste products exhibit more fuel-like characteristics after torrefaction processing commonly seen in briquettes and biocoal production [45]. Torrefaction makes grinding less energy intensive, mitigating emissions associated with transportation and production. Additionally, torrefaction lowers production costs when the technology is more commercially available. Energy products from biomass waste are cost-effective, displace fossil fuels, and have a large range of applications. Therefore, it would also be beneficial to incorporate any remaining EFB or fiber, which is not used in CHP, into biomass energy sources as well.

Table 4 supports that briquetting is both the best option with regards to climate change and economic potential for shells. At this time, charcoal briquettes have a better economic outlook, but activated carbon is a viable option as well. However, the recent implementation of the Power Development Plan in Thailand pushes for "cleaner fuels" that will reduce the country's reliance on natural gas [13]. Under this plan, biocoal is also an attractive pathway for shells due to their ability to produce cleaner electricity compared to

Fig. 8 GHG emissions–empty fruit bunches per reference flow output (reference Table 2)

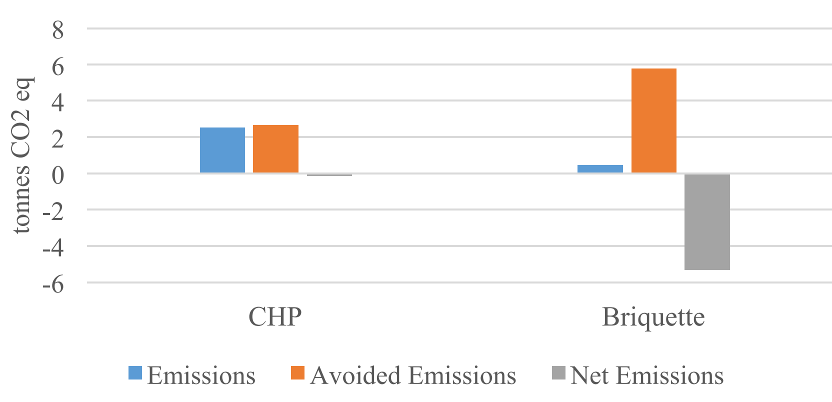


Fig. 9 GHG emissions–palm kernel shells per reference flow output (reference Table 2)

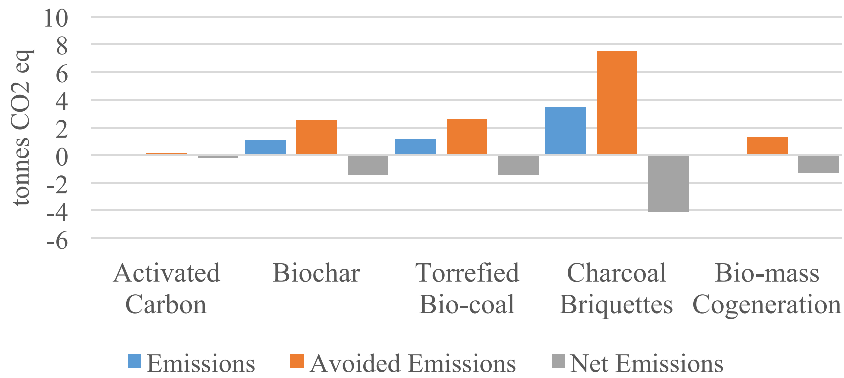
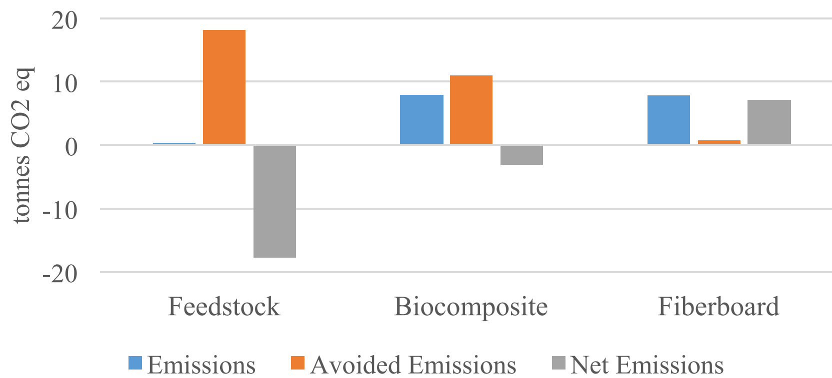


Fig. 10 GHG emissions–mesocarp fiber: per reference flow output (reference Table 2)



conventional fossil fuel-based generation. Currently, large capacity biomass plants in Thailand are scarce, and the majority of the existing plants are only co-firing 5%–10% biomass. Generally, a large plant is necessary to make a profit from policy that incentivizes emission reduction practices [62]. Retrofitting a current coal-fired power plant is about \$300–700/kW for co-feed plants and a \$760–900/kW for separate feed plants [62]. This is cheap compared to constructing a new biomass-only firing plant, but co-firing is still more expensive than coal-firing at this time [62]. Biocoal could become a more feasible pathway in the future with the development of more policy rewarding industrial abatement of carbon dioxide.

3.3 Biocomposites

While it is best for mesocarp fiber to be primarily used for providing power to mills, it could also potentially be utilized for producing natural fiber reinforced biocomposites, though this is not a common practice partly due to the compatibility of the fibers with polymers and moisture absorption [63]. Net GHG emissions were low for the particular biocomposite analyzed in this study since emissions from producing full polypropylene sheets, as opposed to fiber-reinforced polypropylene composites, were avoided. Yet, these avoided emissions could be highly variable due to a wide array of fiber-reinforced composites that may be studied. For both products, emissions were largely

Fig. 11 GHG emissions–fronds per reference flow output (reference Table 2)

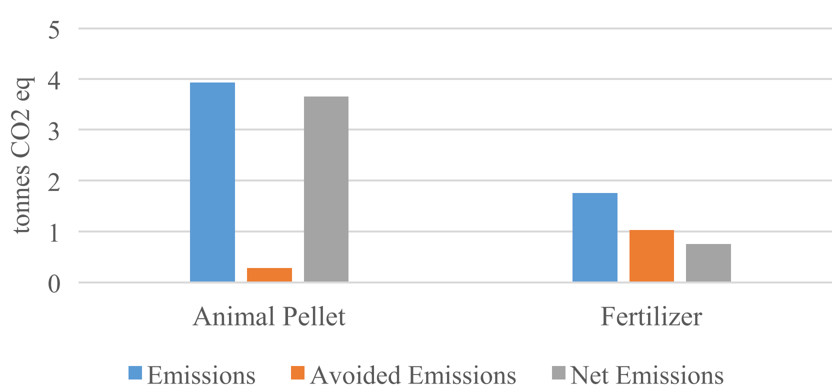


Fig. 12 GHG emissions–trunks per reference flow output (reference Table 2)

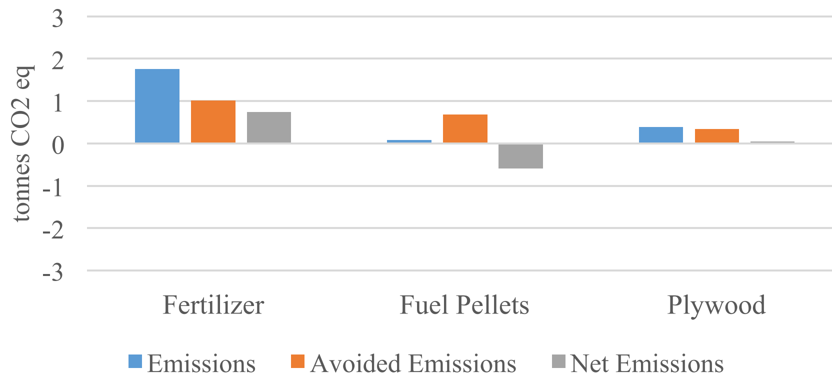
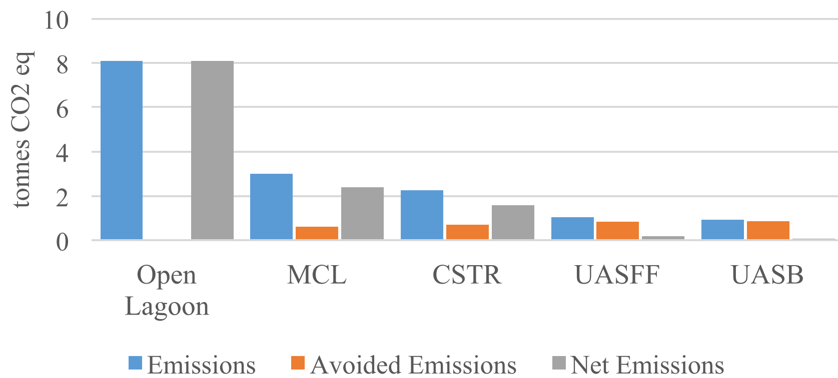


Fig. 13 GHG emissions–POME per reference flow output (reference Table 2)



attributed to polypropylene production. Furthermore, both fiber and oil palm trunks can be used for producing fiberboard and plywood since resulting net emissions for both pathways were also low, as seen in Figs. 10 and 12. These materials from fiber can be used for residential and commercial construction applications such as sound-deadening board, structural sheathing, and roofing substrate, along with other applications in the sporting and automotive industries [33]. However, materials from trunks should not be used in structural building materials due to their high moisture content and inferior strength compared to hard or softwoods but are sufficient for use in non-structural products (such as certain applications of plywood) [12]. Figure 12 shows that substituting oil palm trunks for conventional wood does not create negative net emissions; using trunks for biofuel pellets does yield negative net emissions and thus makes the most sense in terms of global warming potential. Figure 10 displays low net GHG emissions associated with fiberboard since emissions were avoided from the cultivation of wood. Overall, the most favorable option for the implementation of mesocarp fiber is to continue to use it for biomass feedstock, as mentioned above. This pathway displayed a value-added product of 263 USD/reference flow, which was higher than the value-added product of 184 USD/reference flow for the biocomposite. In terms of climate change potential, continuing the use of fronds as fertilizer but using trunks as biofuel instead is the most effective pathway combination to reduce GHG emissions.

Fig. 14 GHG emissions–ethanol pre-treatment options for fronds and EFB per reference flow output (reference Table 2)

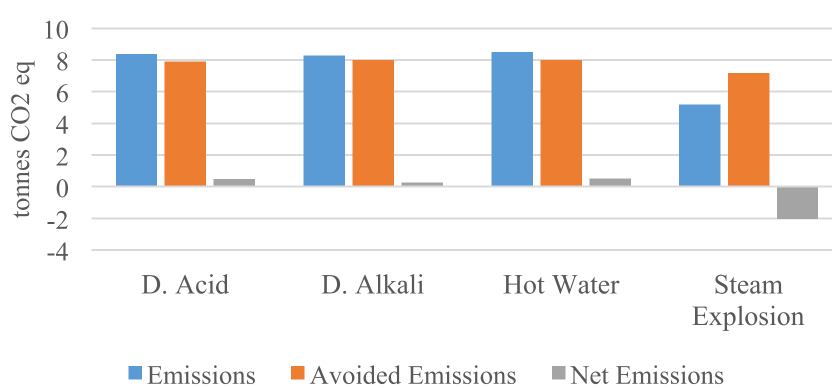


Table 4 Net GHG emissions and added value

Material	Pathway	Net GHG emissions ($t\ CO_2$-eq)	Value added (USD/reference flow in Table 2)	Sources for economic data
EFB	Briquette production	−5.31	231	[47]
	CHP	−0.14	80	[48]
Shells	Activated carbon	−0.17	123	[49]
	Biochar	−1.43	143	[50]
	Torrefied biocoal	−1.45	102	[51]
	Charcoal briquettes	−5.33	660	[47]
	Biomass cogeneration	−1.28	105	[48]
Fiber	Torrefaction for biomass feedstock	−17.68	263	[52]
	Polypropylene biocomposite	−3.09	184	[53] [54] [55]
	Uncoated cellulosic fiberboard	7.10	500	[56] [57]
Fronds	Animal feed pellets	3.65	846	[58] [59]
Trunks	Biofuel pellets	−0.594	11	[59]
	Plywood	0.041	124	[60]
	Fertilizer	0.741	140	[61], [36]
POME	MCL	2.39	104	[13]
	CSTR	1.58	119	[13]
	UASFF	0.191	145	[13]
	UASB	0.077	147	[13]
EFB + Fronds	Dilute acid	0.482	1575	[16]
	Dilute alkali	0.275	1780	[16]
	Hot water	0.516	1517	[16]
	Steam explosion	−2.014	1502	[16]

3.4 Electricity generation

From the methodology stated, the POME treatment system that has the lowest impact on climate change is the up-flow anaerobic sludge blanket (UASB) reactor. The factor that has the largest impact on GHG emissions is the COD removal efficiency of the closed digester. This is because more COD that is removed in the anaerobic digestion stage leads to higher biogas production, thus offsetting more grid-generated electricity. Furthermore, the majority of project emissions come

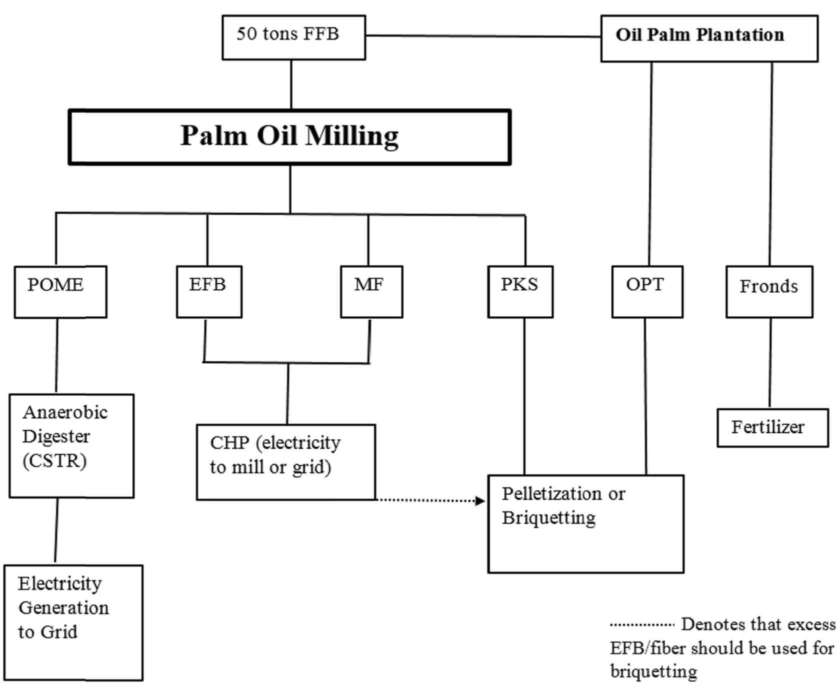


Fig. 15 Final recommended pathways after environmental and economic considerations

from the post-treatment aerobic and facultative ponds that are not equipped with biogas recovery systems, so lower COD content after anaerobic digestion also leads to lower emissions from subsequent ponds. Although the efficiency is slightly lower, the up-flow anaerobic sludge fixed filter (UASFF) reactor should be considered a comparably effective option and may be preferable because it is a hybrid design that utilizes both UASB and fixed filter technology together. The addition of a filter leads to greater stability in the system through better biomass retention, higher operating organic loading rates, and lower susceptibility to shock loading in the system [43]. All of these characteristics are particularly important for treating POME due to the seasonal variations in oil palm production and the high strength of the wastewater. It is important to note that implementing any of the closed-system technologies results in truly significant (70%) decreases in CO_2 emissions compared to using open lagoons.

Although lab studies have shown success of POME treatment in UASB and UASFF reactors, they have not yet been implemented at a large scale due to the high upfront capital cost of high rate reactors, along with the volatility of the system [43]. While these lab-scale studies on high-rate reactors show promise, they were not used for suggesting mill implementations. Based on successful projects in Thailand, available technology options, and associated economic incentives, the best current option is the continuous stirred tank reactor (CSTR) reactor as it is economically attractive while still having emission reduction savings.

For the suggested systems, economics play a vital role in the feasibility of implementation. Emission reduction projects have become more attractive, since under the CDM these projects can earn certified emission reduction (CER) credits that can be traded and sold to increase the economic viability of projects [46]. For example, a CSTR project in Thailand has a lifetime of 20 years with an estimated financial internal rate of return (FIRR) of 6.6%, but including the revenue that can be generated from selling CERs the FIRR increased to 20.0% [44]. On the side of biogas utilization, electricity generation is the main use for biogas in Thailand given the financial incentives provided through the Feed-in Tariff (FiT) system [13]. This system has led to short payback periods on biogas engines, as short as 4.5 years, which encourages further implementation [7]. There are also other available markets, like biohydrogen production and compressed biogas production (CBG) for fuel, which biogas could become a large player in but are less viable until there are technological advances as well as proper support through government policies [64, 65].

4 Conclusion

This study compared various oil palm waste utilization pathways to offer recommendations to mills based on reducing climate change impact and considering economic feasibility. The final recommendations concerning power generation include using POME in a CSTR for biogas recovery and using empty fruit bunch and mesocarp fiber for combined heat and power production. Shells and trunks both have great value as biofuel pellets or as biocoal. Shells also have potential in biochar as activated carbon or fertilizer. Due to the huge amount of fiber and EFB waste, it is recommended that leftover biomass from combined heat and power be pelletized for energy use. Fronds are recommended to remain on the plantation for nutrient recycling. Although some biomasses can serve the same function, through comparing climate change impact and economics *between* pathways, the most appropriate uses are now more apparent. Comparison of multiple pathways for each of several biomasses allows for a novel and holistic review of waste utilization options (Fig. 15).

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