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Alternative Technologies for the Reduction of Greenhouse Gas Emissions from Palm Oil Mills in Thailand

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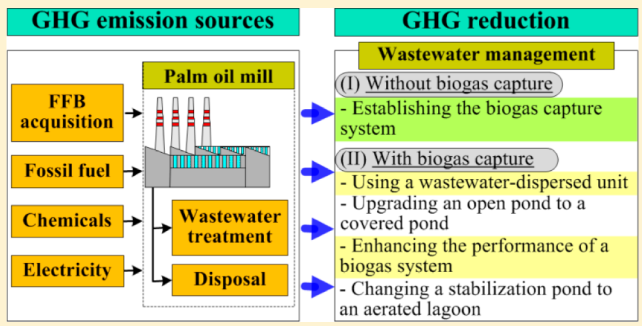
S Supporting Information

ABSTRACT: Alternative methodologies for the reduction of greenhouse gas (GHG) emissions from crude palm oil (CPO) production by a wet extraction mill in Thailand were developed. The production of 1 t of CPO from mills with biogas capture (four mills) and without biogas capture (two mills) in 2010 produced GHG emissions of 935 kg carbon dioxide equivalent (CO_2eq), on average. Wastewater treatment plants with and without biogas capture produced GHG emissions of 64 and 47% of total GHG emission, respectively. The rest of the emissions mostly originated from the acquisition of fresh fruit bunches. The establishment of a biogas recovery system must be the first step in the reduction of GHG emissions. It could reduce GHG emissions by 373 kgCO_2eq/t of CPO. The main source of GHG emission of 163 kgCO_2eq/t of CPO from the mills with biogas capture was the open pond used for cooling of wastewater before it enters the biogas recovery system. The reduction of GHG emissions could be accomplished by (i) using a wastewater-dispersed unit for cooling, (ii) using a covered pond, (iii) enhancing the performance of the biogas recovery system, and (iv) changing the stabilization pond to an aerated lagoon. By using options i−iv, reductions of GHG emissions of 216, 208, 92.2, and 87.6 kgCO_2eq/t of CPO, respectively, can be achieved.



INTRODUCTION

The greenhouse gas (GHG) emission level of the group of countries participating in the Kyoto protocol has decreased 12.4% from the level in 1990. However, the GHG emission of developing countries has continued to rise.[1] The mitigation of GHG emissions by developing countries should be promptly sought. In 2010, Thailand released 0.25 Gt of total GHG from fuel combustion. This value was increased by 209% compared to the level of fuel combustion in 1990.[1] Many related agencies in Thailand should be alert to the urgent need to decrease these levels. To create international credibility, a definite and clear goal to reduce GHG emission is necessary for Thailand.

The palm oil mill industry is one of the most important industries in Thailand. There are two types of mills in Thailand, those with dry and wet extraction processes. The wet process is commonly used in palm oil mills. Fresh fruit bunches (FFBs) from cultivators or collection points are transported to the mill. The crude palm oil (CPO) is the main product, and palm kernels (PKs), shells, and fibers are coproducts. Empty fruit brunches (EFBs) and decanter cakes are classified as waste. For some mills, PKs are pressed to produce palm kernel oil (PKO) as a product. In 2009, ~1.62 million t of carbon dioxide equivalent (CO_2eq) of GHG was emitted via CPO production by a wet extraction process, and the major sources of GHG emission were FFB production and wastewater treatment plants. GHG emission for the production of 1 t of CPO from mills with a biogas capture system was 1039 kgCO_2eq. The installation of a biogas recovery system could reduce GHG emission by 30% compared with the emission of the mills without biogas capture.[2]

GHG emissions for 1 t of CPO production from palm oil mills with and without biogas capture in Malaysia have been analyzed. GHG emissions of the mills with biogas capture were 225 kgCO_2eq/t of CPO. A reduction in the GHG level of 77% was obtained when a biogas capture system was employed.[3] Even though a biogas recovery system was employed, a mill stills emitted GHG in significant amounts to the atmosphere.[2,3] There is a need to investigate options for mitigating this situation.

Many studies have shown that palm oil mills have the potential to reduce their GHG emissions.[4−7] However, methodologies for reducing GHG emission from the wastewater treatment system of the mills with a biogas recovery

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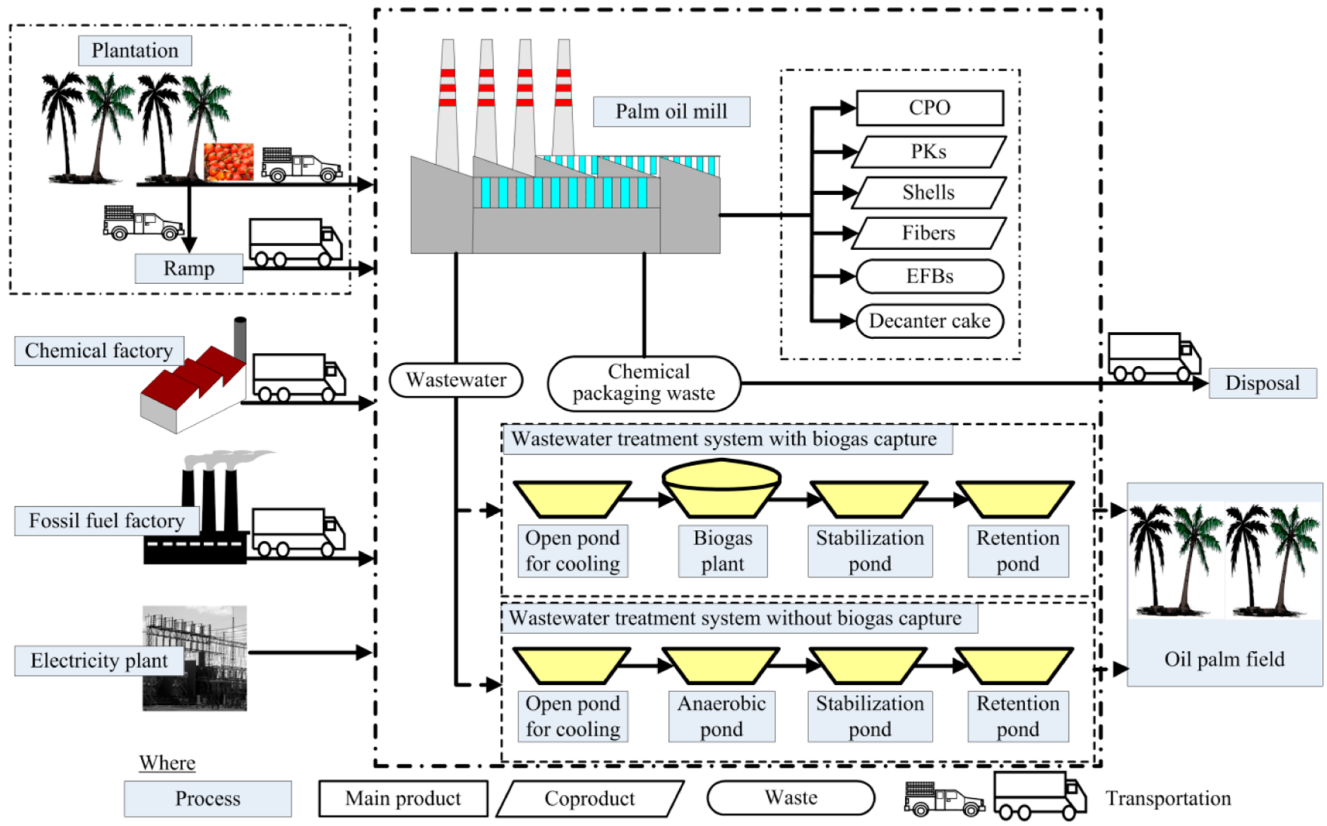

Figure 1. System of this study.

system have never been reported. To promote the sustainable development of a palm oil production, GHG emission from the wet extraction process from the mills needs to be reduced.

METHODOLOGY

Our work was aimed at determining the GHG emission from palm oil mills, developing alternative methodologies for the optimization of GHG emission, and estimating the possible reduction of GHG emission from palm oil mills in Thailand. Six palm oil mills using a wet extraction process with a production capacity of 15−90 t of FFBs/h were selected. Their capacity for CPO production accounted for approximately 11.9% of the total CPO production capacity in Thailand in 2010. The selected mills were located at Chonburi, Phangnga, Krabi, Suratthani, Trang, and Satun provinces. This study uses the GHG addressed by the Kyoto protocol as a reference point.[8]

The values of GHG emission from the mills were divided into two categories according to the wastewater treatment plants. Category I included mills with biogas capture plants (four mills), and category II included mills without biogas capture plants (two mills). The total average of the GHG emission values from six mills and the best observed cases were also analyzed.

This work utilized the methodology developed by Kaewmai et al.[2] for the calculation of GHG emission for the mills. The life cycle assessment (LCA)[9,10] was applied to estimate GHG emission via cradle to gate analysis. The LCA has been used as a tool to determine GHG emission and other impacts of the production of biodiesel from oil palm and Jatropha.[11,12]

The system boundary of analysis included production of inputs, transportation, and the wet extraction process along with the management of generated waste as shown in Figure 1.

The process of CPO production includes sterilization, threshing (separation of palm fruit), digestion, screw pressing, oil extraction, and oil purification (Figure S1 of the Supporting Information). Wastewater was mostly generated from sterilization and oil extraction processes.

We visited each mill to compare the processing step, including the receiving of FFBs, the production of CPO, PKs, and shells, and the wastewater treatment plant. This was done to investigate and confirm that data from mills were obtained by actual measurements as much as possible. All mills have weighing apparatus for determining amounts of FFBs, CPO, PKs, and shells. They used an accounting system for control chemical and diesel uses. The mills used separated electrical meters for measuring the amount of electricity from PEA, a steam turbine, and a biogas plant. Water meters were used to measure the amount of water consumed and the amount of wastewater generated.

Both primary and secondary data were collected in relation to GHG calculation for a period of one year (2010). This included data collected from each mill such as the amount of raw materials, the distance of transportation, and the quantity and quality of wastewater and treated wastewater.

Questionnaires, on-site interviews, surveying, and sampling were used to collect the primary data. The wastewater from processing, the wastewater before and after the biogas capture plant, and the effluent water from the retention ponds were collected from the mills with a biogas capture system. In the case of the mills without a biogas capture plant, the wastewater from processing and the effluent water from the retention ponds were collected. The chemical oxygen demand (COD) of water samples were determined to calculate the GHG emission according to the previous study.[2]

Table 1. Life Cycle Inventory for the Production of 1 t of CPO

parameter	unit	amount (per t of CPO)			
		mills with biogas capture (four mills)[a]	mills without biogas capture (two mills)[a]	average GHG emission (six mills)[a]	best observed case (one mill)[a]
inputs					
FFBs	t	5.92	5.71	5.88	6.49
water consumption in factories	m^3	4.41	5.41	4.59	1.06
electricity consumption from grid	kWh	5.76	52.59	14.36	25.95
diesel oil consumption	L	3.85	3.09	3.71	5.60
chemical usage[b]					
kaolin	kg	12.20	15.17	12.75	12.67
polyaluminum chloride	kg	0.59 (three mills)	0.23 (one mill)	0.53 (four mills)	0.34
anionic polymer	kg	0.002 (three mills)	0.24 (one mill)	0.04 (four mills)	0.01
sodium chloride	kg	0.87	0.51	0.81	4.78
sodium sulfite	kg	0.05 (three mills)	0.03	0.05 (five mills)	0.05
magnesium	kg	0.76 (one mill)	–	0.76 (one mill)	–
soda ash	kg	0.06 (two mills)	0.32 (one mill)	0.10 (three mills)	–
phosphate	kg	0.09 (two mills)	0.03	0.07 (four mills)	–
chlorine	kg	0.09 (two mills)	0.02 (one mill)	0.08 (three mills)	–
outputs					
main product					
CPO	t	1.00	1.00	1.00	1.00
coproducts					
PKO	t	0.13 (two mills)	–	0.13 (two mills)	0.14
PKs	t	0.34 (two mills)	0.27	0.32 (four mills)	
fibers[c]	t	0.40	0.22	0.37	0.71
shells	t	0.35	0.10	0.30	0.41
palm kernel meal	t	0.16 (two mills)	–	0.16 (two mills)	0.17
solid waste					
EFBs	t	0.99	0.83	0.96	0.31
decanter cake	t	0.18	0.11 (one mill)	0.17 (five mills)	0.25

[a]Weighted average. [b]Sodium hydroxide, inhibitor, and a neutralizing amine blend were used in the production in an amount that was <1% of the total chemicals used. [c]Surplus amount from use in a boiler.

The secondary data, emission factors (EFs), and global warming potential (GWP) of the GHG used for calculation in the study were taken from the Thailand Greenhouse Gas Management Organization [public organization (TGO)][13] and the Intergovernmental Panel on Climate Change (IPCC).[14] It must be noted that the potential alternative methodologies for the reduction of GHG emission have been identified and designed without taking the cost into account.

RESULTS AND DISCUSSION

Amount of GHG Emission from Palm Oil Mills. The life cycle inventory for the production of 1 t of CPO is presented in Table 1. The GHG was emitted from various points in the system: (1) indirect emission from the production of inputs (FFBs, chemicals, fossil fuel, and electricity), (2) direct emission from the transportation of inputs to the mill, and (3) direct emission related to production processes and waste treatment at the mill such as on-site fossil fuel combustion, wastewater treatment, and packaging disposal. The contribution values of the GHG emission of the mills in each case are listed in Table 2.

The production of 1 t of CPO in the mills with biogas capture, the mills without biogas capture, the average of six mills, and the best observed case yielded GHG levels of 883, 1164, 935, and 548 $kgCO_2eq$, respectively. The mills with biogas capture emitted GHG at a level 24% lower than that of

Table 2. GHG Emissions of Palm Oil Production by the Wet Extraction Process

emission source	GHG emission[a] ($kgCO_2eq$/t of CPO)			
	mills with biogas capture	mills without biogas capture	average GHG emission	best observed case
(1) FFB acquisition	493	376	471	384
production	438	339	420	336
transportation	54.6	36.8	51.4	48
(2) chemicals	4.57	6.36	4.90	6.77
production	3.49	4.83	3.74	4.58
transportation	0.92	1.35	1.00	1.94
packaging disposal	0.16	0.18	0.16	0.25
(3) fossil fuel	11.5	9.27	11.1	16.8
production	1.05	0.84	1.01	1.53
transportation	0.04	0.06	0.04	0.11
combustion	10.4	8.37	10.0	15.2
(4) electricity consumed from external source	3.23	29.5	8.06	14.6
(5) wastewater from production process	371	744	440	126
total	883	1164	935	548

[a]Weighted average.

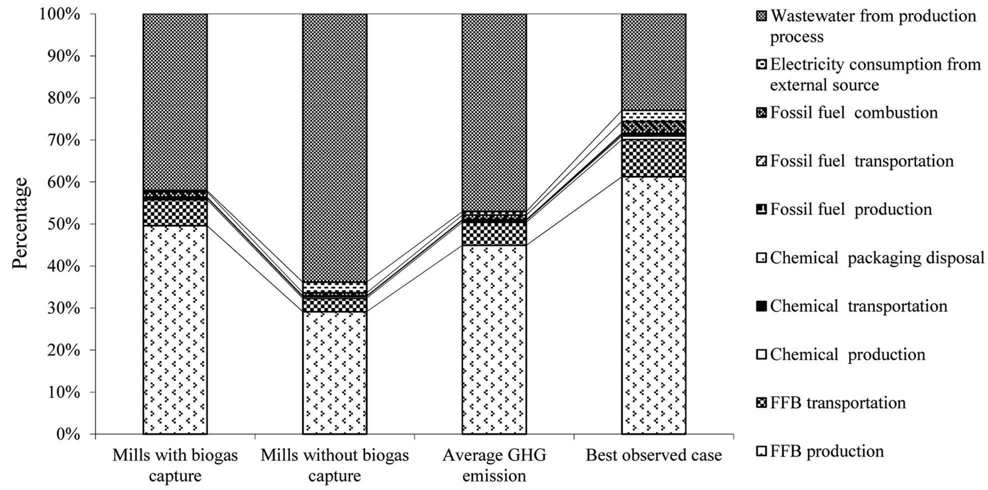

Figure 2. Percentage distributions of GHG emissions from palm oil mills.

the mills without biogas capture. This observation was comparable to that of Kaewmai et al.[2]

The average GHG emission value of 935 $kgCO_2eq/t$ of CPO in Table 2 could be used to calculate the total GHG emission from CPO production in Thailand. This value was lower than an average GHG emission value of 14 wet extraction mills of 1198 $kgCO_2eq/t$ in 2009.[2] An average value of the oil extraction rate (OER) of six mills in 2010 was 17%. The level of FFB production was 8223135 t.[15] This could be converted to a level of CPO production of 1397933 t. CPO production in 2010 yielded GHG emission of 1.31 million t of CO_2eq.

Sources of GHG Emission. GHG emissions had three sources: (1) FFB acquisition, (2) wastewater treatment systems, and (3) processing. The major GHG emission source (Figure 2) for the mills with biogas capture was the FFB acquisition. This was 55.8% of the total GHG emission followed by 42.0 and 2.20% of GHG emission from the wastewater treatment system and processing, respectively. GHG emissions from the mills without biogas capture were observed to be mostly from the wastewater treatment system. This was 63.9% of the total GHG emission, followed by FFB acquisition (32.3%) and processing (3.8%).

The FFB acquisition was the dominant GHG emitting source for six mills. It accounted for 50.4% of the total GHG emission followed by 47.0 and 2.60% of GHG emissions from the wastewater treatment system and processing, respectively. In the case of the mill with biogas capture that had the lowest GHG emission, 70.1% of total GHG emission came from the acquisition of FFBs, followed by the wastewater treatment system (23.0%) and processing (6.9%). In summary, FFB acquisition and the wastewater treatment processes were responsible for >90% of the total GHG emission from the mills. A source of less emission was the use of chemicals, fossil fuel, and electricity in the processes.

FFB Acquisition. By using data in Table 2 in the calculation, the major sources of GHG emission for FFB acquisition were identified as plantation (89.1% of total GHG emission) and transportation (10.9% of total GHG emission). The GHG emissions from the transportation from collection points to the mill, cultivators to collection points, and cultivators to the mills were 6, 4, and 1% of the total GHG emission of FBB acquisition, respectively. The sources of GHG emission in a section of oil palm plantation were (1) the production of inputs such as fossil fuel, agrochemicals, electricity, and organic and inorganic fertilizers, (2) the transportation of inputs to the oil palm plantation, (3) the application of inputs, and (4) waste disposal at the oil palm plantation.[16]

Much GHG emission results from the production and application of organic and inorganic nitrogen fertilizers. These cause the emission of nitrous oxide (N_2O) to the atmosphere.[17] The GWP of N_2O for 100 years is 298 times that of CO_2eq.[18] The optimization of GHG emission from the acquisition of FFBs must be addressed promptly.

Wastewater Treatment Plant. The traditional practice for wastewater treatment is the use of waste stabilization ponds, including anaerobic ponds, aerobic ponds, and retention ponds. Currently, wastewater treatment plants may be upgraded to a biogas system. A gas engine utilizes a biogas to generate electricity for use in the mills. The amount of excess electricity is sold to the provincial electricity authority (PEA) through grid connection. The treated wastewater from biogas plants flows into the stabilization ponds. It is then stored in the retention ponds or discharged into oil palm plantation fields.

In the traditional process, GHG was emitted from anaerobic and unmanaged aerobic ponds. For the wastewater treatment process with a biogas system, the sources of GHG emission were the open ponds used for cooling before the biogas system, the firing of biogas, fugitive emission due to an inefficient biogas capture system, and stabilization ponds used after the biogas system.

The open pond was the main cause of GHG emission (44% of the total GHG emission) in the mills with biogas capture (four mills), followed by 38% from stabilization ponds and 18% from the biogas system. For the mills without biogas capture (two mills), the total GHG emission increased because of only anaerobic ponds and stabilization ponds. The mill that used the wastewater dispersed unit instead of an open pond to cool the wastewater before the biogas system provided minimal GHG emission. The biogas system and the stabilization ponds had the same GHG emission, amounting to approximately 50% of the total GHG emission.

Wet Extraction Process. The major sources of GHG emission were the chemicals used, the fossil fuel used, and the electricity supplied by the PEA. However, mills required smaller amounts of electricity from the PEA. This is because fibers have been used as biomass fuel in the boiler to produce steam for generating electricity for use in the mills. In some mills, there was a diesel generator for starting up the process, but other mills started up the process by using electricity from the PEA.

For the mills with biogas capture, 0.52, 0.37, and 1.30% of the total GHG emission were from the use of chemicals, electricity, and fossil fuel, respectively, as shown in Figure 2. For the mills without biogas capture, 0.55, 2.53, and 0.80% of the total GHG emission were from the use of chemicals, electricity, and fossil fuel, respectively. Considering the average value, GHG emissions of 0.53, 0.86, and 1.19% were generated from the use of chemicals, electricity, and fossil fuel, respectively. In the best observed case, 1.24, 2.65, and 3.07% of the total GHG emission resulted from the utilization of chemicals, electricity, and fossil fuel, respectively.

Alternative Technologies for the Reduction of Emission. *FFB Management.* FFB acquisition accounted for 50.4% of the total GHG emission from six mills. The main cause was the use of nitrogen fertilizer on the oil palm plantation, which accounted for approximately 80% of all GHG emission from the oil palm plantations.[16] Many studies have suggested that a reduction in GHG emission from using nitrogen fertilizer could be accomplished by reducing losses from volatilization, denitrification, leaching, and surface run-off.[19−24]

The application of an osmocote fertilizer could slowly release nitrogen nutrients over a chosen period of time.[25] It could control microbial transformation for slowing N_2O emission.[19] Fertilizers should be fed to plants according to the amount required by the plant to avoid nitrogen in excess of the need of the oil palm. This is because the amount of available nitrogen in the soil correlates with N_2O emission.[26−28]

In general, some nitrogen fertilizer was applied on the surface; hence, fertilization should be performed by directly injecting it into the soil, near the more accessible zone for uptake by roots. This practice could increase the rate of uptake of nitrogen by the oil palm and reduce the rate of loss of nitrogen in the soil, which will result in the mitigation of GHG emission.[29] Furthermore, substitution of an inorganic fertilizer with an organic fertilizer is recommended. Minimal amounts of several nutrients (P, K, N, Ca, Mg, S, Fe, Cu, Zn, Mn, B, and Mo) are included in animal manures. One kilogram of nitrogen nutrients from an inorganic fertilizer could be replaced by 62 kg of animal manure or 57 kg of organic pellet-fertilizer.[16]

Considering the OER from FFBs, if the oil yield in FFBs is increased, the mill will gain large amounts of CPO. The GHG emission per metric ton of CPO, therefore, must be reduced. Cultivators should select and plant the best palm seeds to obtain high-quality FFBs. Moreover, the oil yield through CPO extraction depends on the ripeness of the FFBs. The unripe FFBs contained less oil than the ripe FFBs.[30] Thus, cultivators must harvest the FFBs at the right time and transport it to the mill within 24 h. The mill should provide incentives to the cultivators for supplying high-quality FFBs.

The transport of FFBs to the mill accounted for ∼5.49% of the total GHG emission from six mills. An approach using logistics should be used for the transportation of the FFBs. If the cultivators use pickup trucks to transport FFBs from distant farms to the mill, more GHG emission will occur. If the farms are 10 km from the mill, transportation by a pickup truck will emit 1.84 $kgCO_2eq/t$ of FFBs, while at 30 km, it will generate 5.53 $kgCO_2eq/t$ of FFB. The use of collection points and full loads using 10-wheel trucks for FFB transportation could help to reduce GHG emission by 51.4% compared with GHG emission from transportation by pickup trucks. However, FFBs should be transported from the collection point to mills within 24 h.

Process Optimization. The objective of palm oil extraction is to obtain a high OER from the FFBs. The OER of palm oil mills ranged from 15.2 to 19.3%, and the average OER of six mills was 17.0%. GHG emission from FFB plantations was 420 $kgCO_2eq/t$ of CPO, which means 0.59 million t of CO_2eq/year will be emitted in 2010. The higher the OER, the more CPO will be obtained and the less GHG emission will occur.

With an increase in the OER of 1% from the average percent yield, a reduction in GHG emission of 27.0 $kgCO_2eq/t$ of CPO could be obtained. If the OER is improved to a maximal value at 19.3%, less FFBs will be used to extract 1 t of CPO. Therefore, improving the OER from an average value of 17.0% to a maximal value of 19.3% could reduce the total GHG emission by 12.0% via the acquisition of FFBs. This would equal 0.08 million t of CO_2eq/year in 2010.

Some mills use a diesel engine to generate electricity to start the process. Using electricity from the PEA to start the process could reduce the GHG emission from diesel. The mill generates electricity from a steam turbine for use in the entire process. Fibers have to be used mainly as fuel in the boiler. The boiler must be efficiently operated to save fibers and to sell the remainder to the power plant. Thus, the more fibers sold to the power plant, the greater the GHG reduction that could be obtained from the utilization of fibers as biomass fuel instead of using fossil fuel for electricity generation.

The efficiency of boilers can be improved by utilizing the following techniques. Fibers must be dry, and this will increase their caloric value. An optimal process must be used to minimize the amount of steam used in the processing line. An economizer must be used, and some heat that is lost must be recovered to warm the feedwater or to preheat the combustion air before using it in the boiler. Finally, excellent treatment of water to ensure high-quality feedwater is needed, and an automatic control of blow down is required. This could be because of possible huge energy losses through the blow down process.[31,32]

During processing, oil loss must be monitored and kept under control. Oil loss to fibers, the decanter cake, and wastewater must be minimized to gain additional CPO production. The loss of PKs to the fibers and shells during air separation must be reduced.[31,32]

Many heavy machines are used in the mill, such as a screw press, a decanter, a separator, an EFB presser, and a cutter. All machines must be used to full capacity with minimal empty loads. Improvements in operational procedures and preventive maintenance are needed to ensure that the equipment is efficiently utilized and does not break down. Energy management must be implemented to identify the factors causing poor performance. Action must be taken to find the causes and develop operational guidelines to prevent machines from breaking down. Energy efficient equipment must also be used to replace obsolete equipment.[31,32]

Wastewater Management. *Wastewater Treatment Process without Biogas Capture.* The establishment of a biogas capture system must be the first step in the reduction of GHG emission. The change from an open pond system to a biogas capture system could provide greater efficiency in treating wastewater and producing biogas for the generation of electricity. It could reduce GHG emission from wastewater treatment by 50% for the mill without biogas capture.

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Wastewater Treatment Process with Biogas Capture. The major sources of GHG emission from wastewater of the mill with biogas capture are (1) the open ponds used before the biogas system, (2) firing the biogas and fugitive emission due to an inefficient biogas capture system, and (3) the stabilization ponds used after the biogas system. The variations in the wastewater flow rate, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and wastewater temperature could affect the performance of a wastewater treatment plant. An equalization tank, therefore, is used to overcome these variations. Several wastewater treatment plants of the mills utilize open ponds as an equalization unit to reduce the temperature of the wastewater from approximately 80 to 55 °C. After the temperature decreases, the wastewater is fed into the biogas system.

The average COD of raw wastewater of 93044 mg/L could be decreased by anaerobic degradation in an open pond to 73027 mg/L (Table 3). By calculation, this organic loss was converted to GHG emission of ~216 $kgCO_2eq/t$ of CPO. The biogas system reduced the average COD to 16085 mg/L. GHG emission from the biogas system was 61.5 $kgCO_2eq/t$ of CPO. In the final stage, the stabilization ponds reduced the COD to 4694 mg/L. This could be converted to GHG emission of ~123 $kgCO_2eq/t$ of CPO. The biogas system was the main process capable of reducing the COD by 81% followed by the stabilization pond (71%) and open pond (27%). The average overall efficiency of the system was able to reduce the COD by 95%.

Table 3. Total Annual Amounts of CPO, Wastewater Volumes, Characteristics of Raw and Treated Wastewater, Reduction Efficiencies, and Accumulated Reduction Efficiencies of the Wastewater Treatment Plant with Biogas Capture on the COD

	average value[a]	range from minimum to maximum[b]
total yearly amount of CPO (t)	31297	11840−46251
wastewater volume (m^3/year)	75929	33075−107000
characteristic of wastewater (mg/L)		
COD of influent wastewater	93044	53082−124342
COD of influent into biogas system	73027	52576−92516
COD of effluent from biogas system	16085	3902−31982
COD of effluent from final pond	4694	488−13437
COD reduction efficiency (%)[c]		
open pond for cooling	27	13−40
biogas plant	81	65−93
stabilization pond	71	44−91
COD accumulated reduction efficiency (%)[c]		
open pond for cooling	27	13−40
biogas plant	83	74−96
stabilization pond	96	89−99

[a]The average value of four mills. [b]The values were obtained from each individual mill. [c]The values were obtained from the reduction efficiency of each individual mill.

The aim of this section, therefore, is to provide practical methods for reducing the GHG emission from open ponds, biogas systems, and stabilization ponds used after the biogas system as shown in Figure 3.

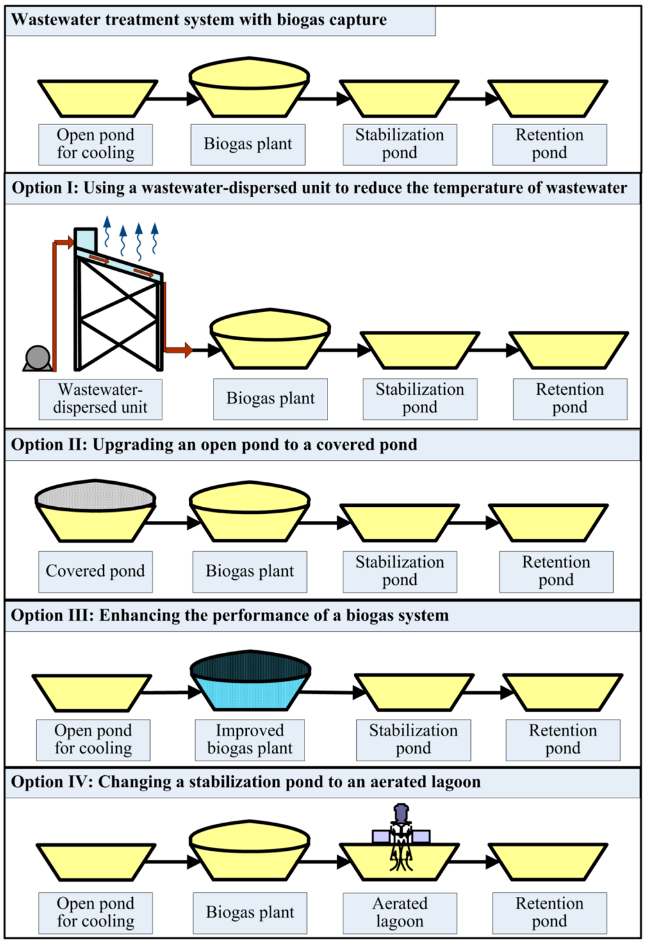

Figure 3. Options for the wastewater treatment process with a biogas capture system.

Option I: Using a Wastewater-Dispersed Unit To Reduce the Temperature of Wastewater. To prevent GHG emission from open ponds before the biogas capture system, a wastewater-dispersed unit can be introduced. Wastewater is pumped and dispersed on the top of this unit that had a large surface area for exchanging heat. By using this unit, GHG emission through anaerobic degradation in an open pond was minimized considerably. However, energy was required to pump the wastewater up to the required level.

Using data in Table 3 in the calculation, the height of a wastewater-dispersed unit was given as 15 m and a 1.5 kW pump was required to operate 24 h/day for 300 days/year. GHG emission of 0.19 $kgCO_2eq/t$ of CPO was generated from the electricity demanded by the use of this unit. Therefore, the total reduction of GHG emission should be 216 $kgCO_2eq/t$ of CPO (99.9%) if a wastewater-dispersed unit is used instead.

Palm oil mill effluent (POME) contains a high level of oil and grease. If the oil and grease are not removed properly from the POME, they could decrease the level of performance of a wastewater-dispersed unit. A setting tank or oil trap must be installed to remove oil and grease from the POME prior to feeding. This is because oil and grease can be removed successfully by an oil trap.[33,34]

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Option II: Upgrading an Open Pond to a Covered Pond. Wastewater was discharged at a temperature of ~65−80 °C. In fact, wastewater can be treated at both thermophilic and mesophilic temperatures to produce biogas.[35] Several researches have shown the practicability of wastewater treatment processes in palm oil mills in thermophilic temperature ranges.[36,37] The treatment of POME using a thermophilic temperature was four times faster or more efficient than that using a mesophilic temperature.[38]

GHG emission from an open pond was 216 $kgCO_2eq/t$ of CPO. By upgrading the open pond to a covered pond, and using biogas for electricity generation, we found GHG emission of ~21.6 $kgCO_2eq/t$ of CPO could come from the fugitive emission. The reduction of GHG emission was 194 $kgCO_2eq/t$ of CPO. The collected biogas could be used to generate electricity by a gas engine. One cubic meter of biogas from POME can generate 2.5 kWh of electricity.[39] Approximately 0.3 m^3 of biogas per kg BOD was removed, or 13 m^3 of biogas/m^3 of POME (9.3 m^3 of methane/m^3 of POME) was measured.[40]

By using the data in Table 3, the amount of biogas and electricity generated could be calculated. The COD/BOD ratio of the POME was ~1.56.[36] It could be used to convert the COD removal of 20017 mg/L in the open pond to BOD removal of 12831 mg/L. This BOD removal was converted to biogas at a rate of ~292283 m^3/year by using the value of 0.3 m^3 of biogas/kg of BOD removed. The amount of biogas produced could be used to generate 730707 kWh of electricity per year. The reduction of GHG emission arising from the replacement of electricity from fossil fuel by electricity from biogas was 13.1 $kgCO_2eq/t$ of CPO. The total reduction of GHG emission via application of this option was 208 $kgCO_2eq/t$ of CPO. However, increasing the efficiency of a covered pond can be achieved by fully recovering oil and grease with the oil trap prior to feeding the POME into the covered pond.

Option III: Enhancing the Performance of a Biogas System. The efficiency of the biogas plant in the mills with biogas capture ranged from 65 to 93% with an average value of 81%. The remaining organic material in this treated wastewater was further treated under anaerobic conditions in stabilization ponds that emitted GHG in significant amounts. Via enhancement of the performance of the biogas system, the level of organic matter in the treated wastewater could be decreased. It could lead to a reduction in GHG emission from anaerobic degradation in the stabilization ponds.

The reduction of GHG emission by enhancing the performance of the biogas system was calculated by using the data in Table 3. Five percent gains in biogas efficiency were used in the calculation, and the base value of biogas efficiency was set at 80%. The practices involved in improving the performance of a biogas system consist of many factors. The major factors are pH, the nutrients for bacteria, the temperatures used in the operation, the mixing, and the rates of addition of organic matter into the digester.[35] The pH should be maintained near 7.0, and the COD:N:P ratio during startup should be 300:5:1. During steady state operation, the COD:N:P ratio could be decreased to 600:5:1. In addition, the optimal temperature for operating using the biogas is divided into two ranges: (1) 25−38 and (2) 50−70 °C. An alkalinity range from 2000 to 4000 mg/L as $CaCO_3$ is typically required.[41]

The production of the biogas in larger quantities and the greater methane composition from POME by using an anaerobic sequencing batch reactor (ASBR) could be achieved with high organic loading, a shorter cycle time, and a longer hydraulic retention time. Therefore, it is necessary to expand the size of the biogas system so that the POME can remain in the system longer.[42]

A summary of the GHG emission upon enhancement of the performance of the biogas system is presented in Figure S2 of the Supporting Information. Via an improvement in the efficiency of the biogas system from 65% to the base value of 80%, GHG emission is reduced by 106 $kgCO_2eq/t$ of CPO. When the efficiency is increased from 65% to the highest value of 93%, GHG emission is reduced by 199 $kgCO_2eq/t$ of CPO. Furthermore, increasing the efficiency from the base value of 80% to the highest value of 93% could reduce GHG emission by 92.2 $kgCO_2eq/t$ of CPO.

Option IV: Changing a Stabilization Pond to an Aerated Lagoon. An aerated lagoon is introduced for use instead of a stabilization pond. By using an aerated lagoon, the anaerobic degradation in the stabilization pond could be avoided. The methane correction factor of aerobic treatment is divided into two cases: (1) well managed and (2) poorly managed or overloaded.[14] A well-managed aerobic treatment is considered in this study. When an aerated lagoon is used, it requires electricity for the operation of the aerators. In the calculation, the oxygen requirement for wastewater treatment in the aerated lagoon was 166 kg of O_2/h. Aeration equipment using 150 kW was required. It must be operated for 24 h/day and 300 days/year. The electricity consumption for running this equipment must be taken into account in the calculation of GHG emission. The calculation shows that the stabilization pond yielded GHG emission of ~107 $kgCO_2eq/t$ of CPO, whereas the aerated lagoon yielded GHG emission of 19.4 $kgCO_2eq/t$ of CPO. The total reduction of GHG emission is equal to 87.6 $kgCO_2eq/t$ of CPO or 81.9%.

■ ASSOCIATED CONTENT

Supporting Information

Diagram of the wet extraction process (Figure S1) and GHG emission from biogas capture and stabilization ponds based on the efficiency of a biogas capture system (Figure S2). This material is available free of charge via the Internet at http://pubs.acs.org.

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