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OPTIONS FOR ENVIRONMENTAL SUSTAINABILITY OF THE CRUDE PALM OIL INDUSTRY IN THAILAND THROUGH ENHANCEMENT OF INDUSTRIAL ECOSYSTEMS

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Abstract. The crude palm oil industry plays an important role in the economic development of Thailand and in enhancing the economic welfare of the population. Despite obvious benefits of this industrial development, it also significantly contributes to environmental degradation, both at the input and the output sides of its activities. On the input side, crude palm oil mills use large quantities of water and energy in the production process. On the output side, manufacturing processes generate large quantities of wastewater, solid waste/by-products and air pollution. Current industrial wastes and recoverable materials are empty fruit bunches, fibers, shells and ash. It is estimated that in 2003, a total of 2.1 million ton of solid wastes/by-products and 2.5 million m^3 of wastewater were generated. The concept of the industrial ecosystem points at the potential of industrial waste recycling resembling food chains, food webs and nutrient cycles of nature. Following the notion of industrial ecology crude palm oil mills can develop a number of waste recycling and reuse systems. This paper analyzes the nature of these industrial ecosystems, divided in in-plant ecosystems (clean technology options) and external waste exchange between crude palm oil industries and other economic activities in Thailand.

Key words: clean technology, crude palm oil industry, industrial ecosystem, Thailand, waste exchange.

Abbreviations: BOD: – Biological oxygen demand; CPKO: – Crude palm kernel oil; CPO: – Crude palm oil; EFB: – Empty fruit bunches; FFB: – Fresh fruit bunches; GHG: – Green house gases; POME: – Palm oil mill effluents; TKN: – Total Kjeldahl nitrogen

1. Introduction

Waste handling is the final and critical step for industrial pollution control. Although cleaner production is generally seen as a more integrated approach than abatement of industrial pollution by means of end-of-pipe solutions, the former is still restricted to

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only one production process or one factory. In the concept of industrial ecology, an industry – with its relations to other industries and economic actors – is considered an industrial ecosystem (Ayres and Simonis, 1994; Graedel and Allenby, 1995; Allenby, 1999). This concept focuses on the relations among companies in a direct waste/by-product exchange (Frosch and Gallopoulos, 1989). The benefits of waste exchange include: reduction of disposal costs, reduction in the demand for natural resources, reduction of quantities for final disposal and a potential increase in the economic value of waste (USEPA, 1992). Through using different system boundaries industrial ecology can be applied to industry development at three levels: micro-level (firms), meso-level (eco-industrial parks), and macro-level (regional and wider global networks of manufacturing activity centers) (Roberts, 2004). In practice, industrial ecology seems to work best where there is a strong agglomeration or clustering of firms that have the capacity to utilize waste as a resource in their production process. In Asian developing countries, the application of industrial ecology takes place especially in industrial estates (Chiu and Yong, 2004).

The palm oil industry plays an important role in Thailand's economy. Palm oil occupies 70% of the Thai vegetable oil market, and is estimated to be worth 40,000 million Baht per annum and has known an average annual growth rate of 15% during the last decade. In 2003, the production of palm oil was estimated to be 680,000 tons. It is expected that in 2006 the national consumption will increase up to 718,000 tons. In 2003 there were 25 wet-process crude palm oil factories in Thailand, producing about 0.7 million ton of crude palm oil from 4 million ton of fresh fruit bunches (FFB). These factories are located in the southern part of Thailand and are traditionally regarded as the major consumers of water and the major sources of organic pollution of surface water bodies. Palm oil production generates large amounts of process residues such as fibers (6.0×10^5 ton/year), shells (2×10^5 ton/year), and empty fruit bunches (9.0×10^5 ton/year). A large fraction of the fibers and much of the shells are utilized as fuel to generate steam and electricity in the palm processing mill itself. However, much is also wasted by dumping in areas adjacent to the mill, or utilized as fertilizer in the palm oil plantation.

Currently, recycling and recovery of input resources are becoming among the highest concerns for the industry. Therefore the crude palm oil industry is developing a number of industrial ecosystem practices for waste recycling. The objective of this study is to illustrate an application of clean technology and of the industrial ecology concept at the factory level as a contribution to a more sustainable industrial development in the Thai crude palm oil industry.

2. Methodology

All the palm oil factories in Thailand have a more or less similar production process. Their production capacity varies between 25 and 60 ton of FFB per hour. The annual production capacity varies even wider, between 63,000 and 420,000 ton FFB, depending on the number of hours the factory is operating, varying from 8 to 24 h per day. After an overall study of the palm oil processing industry in Thailand, five companies applying wet processes have been selected for a more detailed analysis of their application of clean technology options. Besides criteria such as availability of data and access to companies, the differences in production processes and locations have been taken as core selection criteria. The factories are classified into three groups, depending on their production technologies:

- Factories using improved processes: use of decanter and separator for oil recovery. These processes currently represent the best practice in clean technology in Thailand.
- Factories using standard processes: the use of decanter for oil recovery. Applying this technology represents a good improvement in clean technology.
- Factories using the standard process: a separator is used for oil recovery. This choice represents a minimal implementation of cleaner production processes.

The general data for the five selected factories (factory A to E) such as location, production capacity, production process, and quantities produced are summarized in Table I.

The methodology used in this study can be divided into five main steps:

Step 1: Analysis of the existing production processes.
Step 2: Analysis of material and energy flows.
Step 3: Selection of appropriate possibilities for prevention and minimization of waste generation.
Step 4: Identifying and designing the potential internal and external recycling and reuse options.
Step 5: Analysis of appropriate final waste treatment.

3. Results of the Study

3.1. Production Process

The two main products derived from the oil palm fruit are crude palm oil (CPO) and crude palm kernel oil (CPKO). CPO is obtained from the mesocarp (fiber) and CPKO is obtained from the endosperm (kernel). Each oil mill applies a conventional oil milling process, beginning with the steaming of FFB under high pressure (sterilization) for a prescribed period of time to condition the fruits. The sterilized bunches are then threshed to separate the fruits from the bunch stalks. The fruits are subsequently pressed to obtain the crude oil. This oil–water mixture undergoes a separation process before the oil is purified and dried prior to storage. The water phase forms the bulk of the raw palm oil mill effluent, which is treated in a wastewater treatment plant or a treatment pond. Figure 1 shows the schematic diagram of factory A (as illustration of a factory representing the best technological practices).

TABLE I. Comparison of general data of 5 selected factories.

	Factory A	Factory B	Factory C	Factory D	Factory E
Location	Close to community	Far from community	Close to community	Far from community	Far from community
Production capacity (ton/h)	45	60	40	60	30
Investment costs (million Baht)	180	142	90	183	97
Available clean technology options	Best practice	Best practice	Good practice	Good practice	Poor practice
Reason for clean technology adoption	Increase oil yield Minimize waste Reduce water use	Increase oil yield Minimize waste Reduce water use	Minimize waste Reduce water use Comply with the law	Increase oil yield Minimize waste	–
Initial oil recovery from WW	Decanter & separator	Decanter & separator	Decanter	Decanter	Separator
ISO certification	ISO 9000	ISO 9000	ISO 9000	–	–

3.2. Production Efficiency

In 2003, there were 0.3 million ha of oil palm plantations in 14 southern provinces of Thailand. The oil palm plantations in Thailand are planted with a density of 150 oil palms per hectare. The current yield generally varies between 14 and 18 tons of FFB per hectare per year (on average 16.5 tons of FFB per hectare per year). The average total production for an average planting cycle of 25 years is 413 ton FFB per hectare. The average content of oil in oil palm fruit is 17%. The FFB production is approximately 4 million ton FFB per year, but the maximum production capacity for all 25 wet-process factories in Thailand is approximately 740 ton FFB per hour

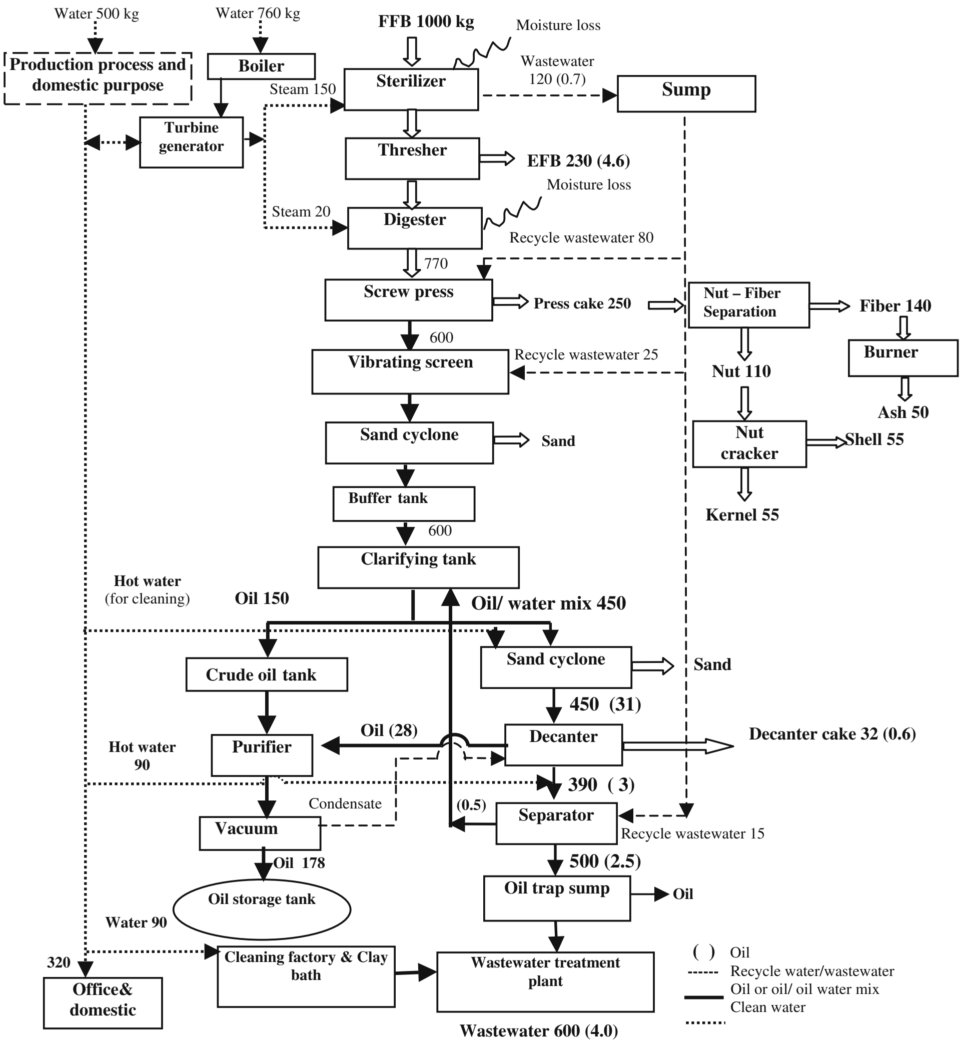

Figure 1. Mass balance (in kg) of production process of a study factory.

or 5.3 million ton FFB per year (with 300 operational days per year at 24 h per day). Therefore all factories currently operate at an average of 75% of their full capacity.

CPO production efficiency in Thailand is 16.8% as shown in Table II. The oil yield of Thai oil palm plantation is 2.75 ton/ha/year.

3.3. Environmental Problems

The entire crude palm oil process does not need any chemicals as a processing aid. However, there are a number of environmental problems at the factories, such as high water consumption, the generation of a large amount of wastewater with a high organic content, and the generation of a large quantity of solid wastes and air pollution. An overview is given in Table III.

Figure 2 shows the waste generation (per ton FFB production) from the crude palm oil industry in Thailand. Results from this study show that only 22.8% of the raw material input consists of valuable products (CPO and CPKO); the rest is considered by-product and waste. Most of these by-products can be sold or reused in the palm oil production process itself or by other industries such as the use of fibers (14%) as fuel in a boiler. Shell (6%) and empty fruit bunches (EFB) (24%) can be sold to other industries. However, there is a lot of waste that has to be treated properly before disposal or discharge. These wastes include 640 m^3 of wastewater, ash (4.8%), and decanter sludge (4.2%).

3.3.1. *Solid waste generation*

In 2003, Thailand's crude palm oil industry produced 0.7 million ton palm oil per year. Crude palm oil production generates large amounts of process residues such as fibers (0.6 million ton per year), shell (0.2 million ton per year), and empty fruit bunches, EFB, (0.9 million ton per year). These residues such as EFB and shells are already reused/recycled as solid fuel. However, there are also other potential options to use these residues as a more valuable product. These options are reviewed in the next section. For wastes, which are currently disposed of such as decanter sludge and ash, other more sustainable solutions for are also discussed based on recent research in Thailand.

TABLE II. The average values of raw material and waste generation from five selected factories in Thailand (2002).

	Wet weight (ton/ha/year)	Dry weight (ton/ha/year)
Fresh fruit bunch	16.5	10.6
Oil yield	2.75	2.75
Oil content in oil palm fruit (%)	17	–
Oil extraction (%)	16.8	–
Empty fruit bunch	3.96	2.6
Fiber	2.31	1.6
Shell	1.0	0.9
Wastewater	10.56	0.64

3.3.2. *Wastewater generation*

In the wet-process in the palm oil production system, high quantities of water are utilized during the process of crude palm oil extraction. Results from this study, show that water consumption in these production processes is in the range of 1.0–1.3 m^3/ton FFB. About 50–79% of the water used results in palm oil mill effluents

TABLE III. Summary of the emissions associated with the crude palm oil production.

Process	Air emission	Wastewater (WW)	Solid waste
Loading ramp	–	Oil contaminated WW	–
Sterilization	Steam blow down	High organic WW	–
Bunch stripping	–	–	Empty fruit bunch
Oil extraction	–	–	Fiber, shell
Oil clarification	–	High organic WW	Decanter cake
Oil purification	Vapor	High organic WW	–
Steam generation	Particulate matter	–	Ash

Note: WW, Wastewater.

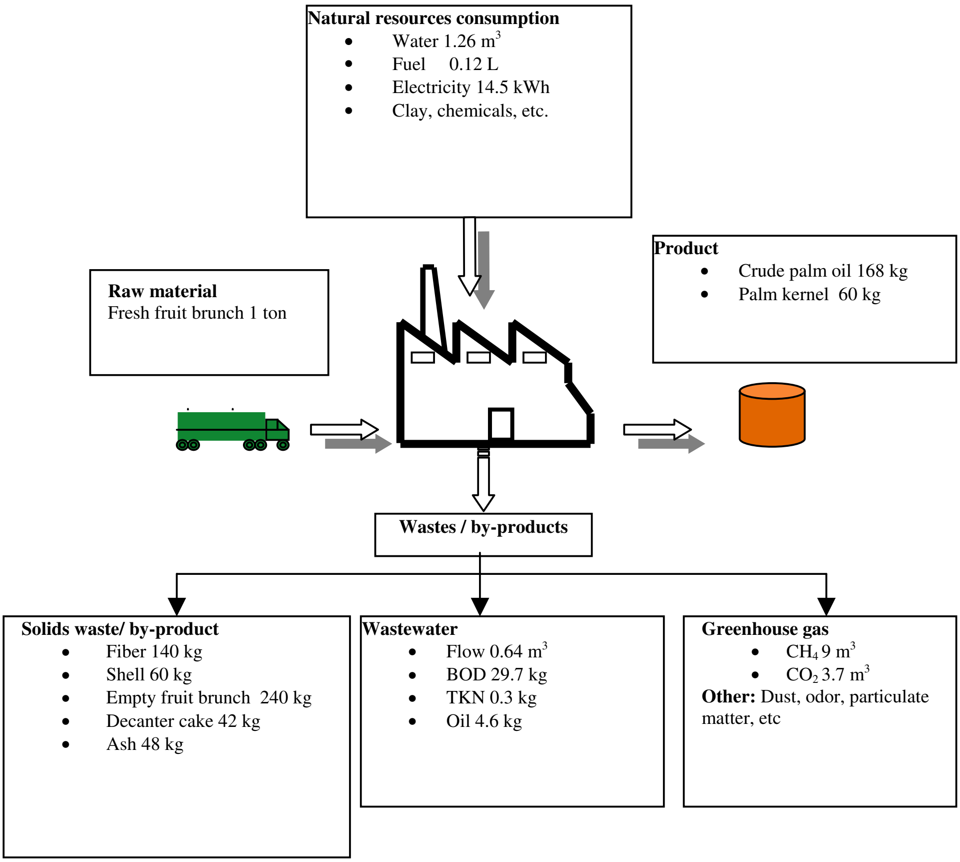

Figure 2. Average value of waste generation rate (per ton FFB) from five selected crude palm oil mills.

(POME). The remainder is lost as steam, mainly through exhaust gases from the sterilizer. It can be estimated that the total wastewater generation and BOD load resulting from palm oil mills in Thailand in 2003 was equal to 2.56 million m^3 and 118 million kg, respectively. In terms of BOD this amount is equivalent to the amount of municipal waste water that is generated by 5 millions people (per year).

3.3.3. *Green house gases*

The anaerobic ponds in the wastewater treatment systems produce methane and carbon dioxide. These are released as gases into the air. Carbon dioxide and methane are both so-called green house gases (GHGs), which may contribute to global warming. Results from analyzing the quantities of GHGs produced from an anaerobic pond showed that the amount of methane and carbon dioxide generated are about 9 and 3.7 m^3/ton FFB, respectively.

3.4. Existing Industrial Ecosystems in the Crude Palm Oil Industry

The crude palm oil industry has developed a number of industrial ecosystem practices for its waste recycling. The nature of these practices can be divided into in-plant industrial ecosystem (clean technology) options and possibilities for external waste exchange, which includes recycling of wastes between the industrial sector and other sectors such as agriculture. The various technical options for an industrial ecosystem approach are shown in more detail in Figure 3.

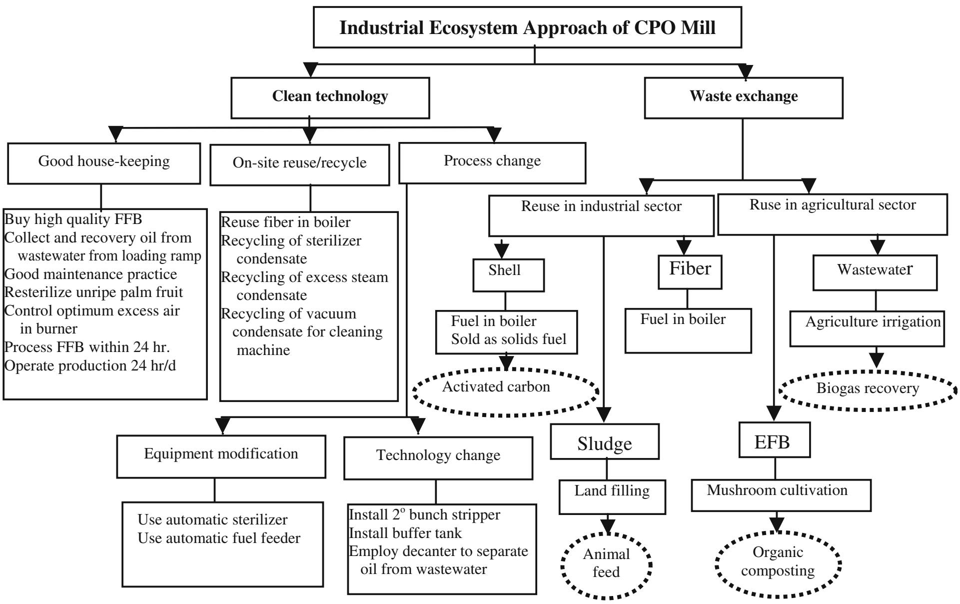

Figure 3. Waste management for improving environmental performance of crude palm oil. [solid box], Existing options; [dotted outline], Proposed options.

3.4.1. *In-plant industrial ecosystem practices (clean technology options)*

The selected options for on-site reuse and recycling are presented in more detail in the following sections. The data presented are based on the results of the five selected crude palm oil mills in this study.

Recycling of fiber and shell in boiler. Thai palm oil mills operate a cogeneration system using fiber and shell as fuel in a boiler to produce high pressure steam which is expanded through a steam turbine to produce electricity. The low pressure steam is used in the manufacturing process for sterilization, digestion, purification and also for temperature control. The electricity generated is used to supply almost all of the electricity requirements for the mill, which is estimated to be about 14.5 kWh/ton of fresh fruit bunch processed. Based on 1 ton processed FFB, 140 kg of fibers and 30 kg of shell are burned to supplement the steam required in production process. The gross caloric value of fiber and shell are 17,422 and 19,462 kJ/kg, respectively.

Recycling of sterilizer condensate. After use for production of electrical power from the turbine, the low pressure steam is sent to the sterilizer. Sterilization of FFB is done batch wise in an autoclave with a capacity of 20–30 ton FFB. The required amount of sterilization condensate is about 0.12 m^3/ton FFB. The slightly polluted condensate obtained can be recycled to the screw press and the vibrating screen in order to reduce the amount of hot water required in these processes. This

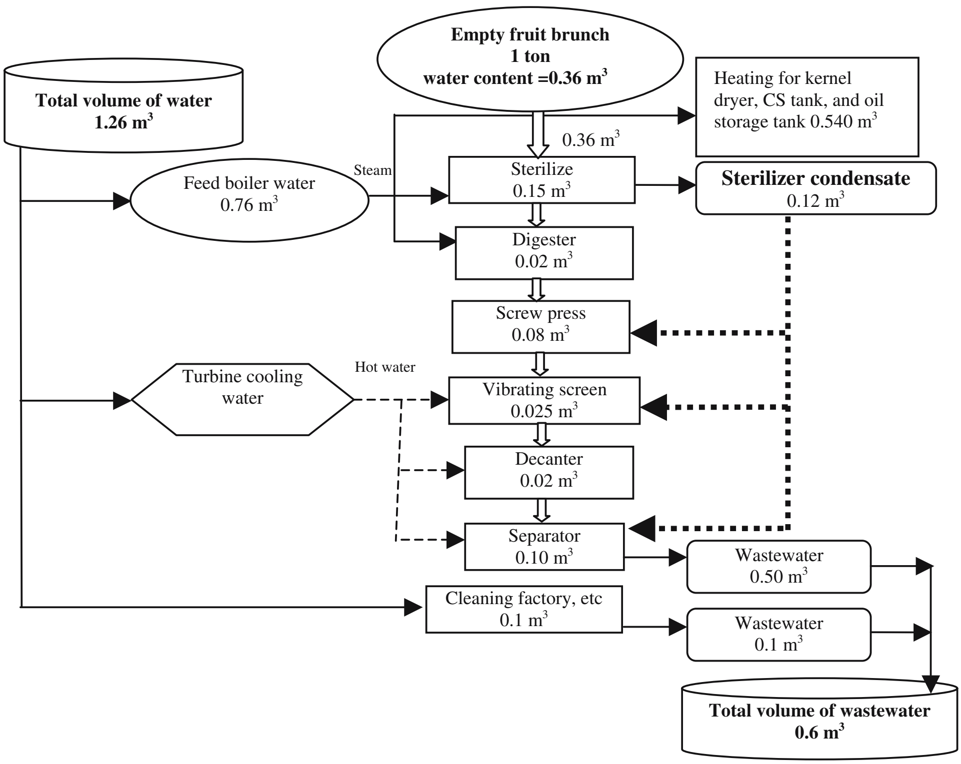

Figure 4. Flow diagram of production process and in-plant water recycles (volume per ton FFB).

is shown in Figure 4. Moreover, the sterilizer condensate contains about 0.6% oil which can be recovered as crude oil in the clarifying tank. This option can save costs of water production of about 0.30 Baht/ton FFB. The recovery of oil from recycled wastewater is about 0.7 L/ton FFB. Benefits from the increased oil yield amount to 7 Baht/ton FFB. The total profit for this option is about 7.3 Baht/ton FFB.

Recycling of excess steam condensate. A certain amount of the steam from the turbine is sent to the kernel dryer silo for drying kernels. Condensate from the kernel dryer is reused as feed boiler water. This option will reduce the amount of water consumption and wastewater generation. An additional benefit comes available from this approach because energy is saved for heating the water to 90 °C (Figure 5). It is estimated that about 0.030 m^3 water per ton FFB could be saved by recycling the excess condensate. Another option is the reuse of condensate from the vacuum dryer for cleaning the decanter and separator.

3.4.2. *Waste exchange (options)*

Recycling of wastes within the industrial sector. Shells as fuel for cement factories. As already mentioned, shells can be used as boiler fuel in the factory. Palm oil mills prefer fibers as fuel in their production process, because they generate dust while their bulkiness makes transport difficult. As more than enough fibers are available for use in the boilers, the shells are sold to be used as fuel in cement and brick factories. Another possible use of the shells is in the production of charcoal. One ton of shells has a market value of about 500 Baht.

Recycling of wastes in the agricultural sector. EFB as a substrate for straw mushroom cultivation. Currently, EFB is returned to the palm oil plantation area. The factory can sell EFB for 600 Baht/ton. Oil palm producers use EFB as a substrate for the cultivation of straw mushrooms in the oil palm plantation area. About 30 kg of mushrooms can be harvested from 1 ton of EFB and sold for 45 Baht/kg mushroom. After harvesting the mushrooms, the EFB substrate is available for fertilizing the oil palm plantation area.

Palm oil mill effluent (POME) for agricultural irrigation. Application of biologically treated POME for irrigation is used by many palm oil mills, which are located in the plantation area. As Table IV shows, wastewater is suitable for oil palm

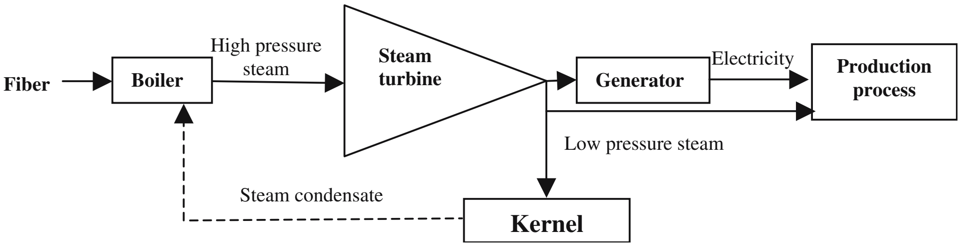

Figure 5. Recycling of condensate to boiler.

TABLE IV. Average nutrient content in the treated POME.

Nutrient component	N	P	K	Mg	Quantity
Raw wastewater (kg/m^3)	1.1	0.047	0.1–0.3*	2.0*	640 m^3/1000 ton/d
After anaerobic treatment (kg/m^3)	0.34	0.028	0.1–0.3*	2.0*	
After full anaerobic treatment (kg/m^3)	0.03	0.003	0.1*	2.0*	
Amount of nutrients in wastewater after anaerobic treatment (ton/300,000 ton FFB/year)	64.3	5.3	37.8	378	

*Data from Kittikhun et al. (1996).

irrigation after anaerobic treatment because it is neutral (pH ~7.8) and still contains high N, P, K and Mg contents. From calculations based on the processing of 300,000 tons of FFB per year it appears that the annual nutrient amounts in wastewater after anaerobic treatment are equal to 64.3, 5.3, 37.8, and 378 tons of N, P, K, and Mg, respectively.

Biogas recovery from wastewater. From the results obtained from studies on biogas production using POME in Thailand both on a pilot plant scale and on full-scale plant experiments, it has become clear that the use of a completely mixed anaerobic digestion tank with a capacity of 2,300 m^3 for treating wastewater from a palm oil mill at a flow rate of 300 m^3/day can generate 6,000 m^3 biogas (60% methane) per day (Kochapansunthorn, 1998; BOSCH, 2004). The biogas can be used as fuel in a boiler for generating steam and electricity, for use in a production process, or for electricity generation in general. The use of methane for power generation could be considered, but most palm oil mills are self-sufficient in power, so the option of using biogas for energy production in the palm oil industry has not been applied yet.

3.4.3. *Existing industrial ecosystem in the crude palm oil industry*

Figure 6 presents a schematic diagram of a crude palm oil mill. For purpose of an evaluation, the estimated mass balances are based on the processing of 1000 tons of fresh fruit bunch, harvested from 18,000 ha of oil palm plantations and producing 168 ton of crude palm oil and 60 ton of palm kernel oil for selling to the oil refinery industry. The production process results in the generation of about 640 m^3 of wastewater, 240 ton of empty fruit bunches, 140 ton of fiber, 60 ton of shell and 42 ton of sludge from the decanter. Most of these by-products can be sold or reused in the production process itself or sold to other industries. However, a lot of waste remains that has to be treated properly before disposal. These wastes include 640 m^3 of wastewater, and furthermore ash and decanter sludge. For the disposal of the solids wastes decanter sludge and ash, the factory has to pay for truck transport every day because they cause bad odors and dust, which constitute a nuisance to the people living in the areas surrounding the factory.

3.5. Improving the Environmental Performance of Crude Palm Oil Mills

In this section possible solutions will be presented with regard to the existing environmental problems of palm oil factories. The options proposed here aim at

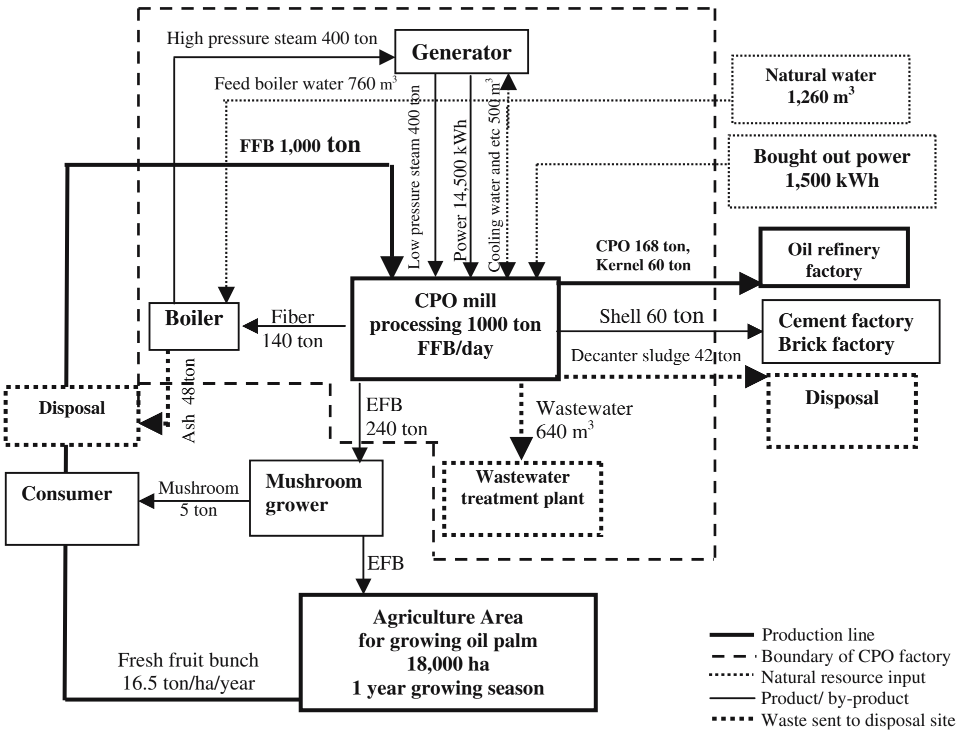

Figure 6. The existing industrial ecosystem model of crude palm oil mills that are situated closed to community.

improving the environmental performance of these factories and also to make palm oil production in Thailand more sustainable. Based on the results from many research projects both in Thailand and Malaysia we can identify possible solutions that can be implemented easily (Kittikun et al., 1996; Panyawathanakit, 1997; Kochapansunthorn, 1998; Suravattanasakul, 1998; Minsirinun, 1999; Unapumnuk, 1999; Ramli et al., 2002; Husin et al., 2003; BOSCH, 2004).

3.5.1. *Production of valuable material*

Shells as material input for activated carbon production. Palm shells have properties similar to coconut shells and the B.E.T. surface area and iodine number show that shells have high number of pores similar to coconut shells. Therefore, the shells are likely to be a precursor for the production of activated carbon. The various processes for activated carbon production from oil palm shells, which have been investigated in Thailand, are shown in Table V. The characteristic aspects of commercially produced activated carbon from coconut shells are also given. According to the table, it is evident that the yield of activated carbon prepared by zinc chloride activation is 14% higher than when prepared by steam. However, the chemical costs of the zinc chloride activation method are very high compared to the steam activation method or commercial coconut or palm shell activated carbon.

TABLE V. Properties of activated carbon from palm kernel shell compared to coconut shell.

Description	Minsirinun (1999)	Suravattanasakul (1998)	Panyawathanakit (1997)	Commercial coconut shell
Carbonization	400 °C for 1 h	750 °C for 3 h	400 °C for 1 h	–
Activation	800 °C for 3 h with zinc chloride	Steam	Steam	–
Yield (%)	33.83	12.18	19.31	18.8
Iodine number (mg/g)	1069	767	779	976
Methylene blue number (mg/g)	600	189	137	500
B.E.T. (m^2/g)	1099	670	697	900

Decanter cake as animal feed. Dry decanter product can be converted into commercial grade pellet animal feed. In order to be able to sell the wet decanter cake to a feed mill, this by-product has to be dried. This can be done through the use of low pressure steam from the boiler with a temperature of 210 °C as a heating medium to dry the decanter sludge into a cake with a moisture content below 10%. An indirect, horizontal dryer could be used to dry the decanter solids to a low moisture content (90% TS). The temperature of the dryer exhaust gases is about 100 °C. The dry decanter product can be converted into commercial grade animal feed pellets.

Alternative use/recycle of empty fruit bunches. Composting is used to produce organic fertilizer from empty fruit bunches. Composting this by-product results in 50% reduction of both the volume and the transportation costs of empty fruit bunches. Unapumnuk (1999) investigated the composting process for a complete mixture of EFB, decanter sludge and urea (as N source). It was a batch process carried out in heaps which were piled up into a size of 2 m×2 m×1 m and covered with plastic. The composting piles had to be turned at regular time intervals. Water was sprayed to control the moisture content at 50–60% in the composting process. The composting piles, that had been set up at an initial C:N ratio of 39:1, showed a rapid degradation rate and maturated in 80 days. The maturate compost contained N, P_2O_5 and K_2O equal to 2.26%, 3.3% and 2.25% of the total matter, respectively. The economic value of the nutrients in the compost in case they would replace chemical fertilizers was equal to 135,529 Baht/1000 ton (prices at wholesale market in Bangkok, 1991).

Reuse of biogas. The average quantity of wastewater generated from a CPO mill in Thailand amounts to 0.64 m^3/ton FFB. This means that about 2.6 million m^3 of wastewater needs to be handled every year. Fresh POME is acidic and contains a high concentration of organic and suspended matters, and is always discharged to a treatment pond at a temperature of 60–80 °C. The BOD:N:P ratio on a weight basis is equal to 100:1.9:0.07. Results from the measurements at one of the studied factories showed that the composition of the gas generated in the first anaerobic pond is about 71% methane and 29% CO_2. It is estimated that biogas generation amounts to 0.3 m^3/kg BOD removed or 8.5 m^3/ton FFB (6 m^3 methane/ton FFB). Compared with a mill with a capacity of 45 ton FFB/day, the conversion of biogas to electric energy using gas-engine generators with a capacity of 300–400 kW, the whole CPO industry in Thailand could generate electricity with an amount of 40 million kW/year (BOSCH, 2004). In fact, the mill could sell electricity to the Electricity Generation Authority of Thailand. Another benefit of anaerobic treatment is the reduction of BOD with 95.5%. The construction costs of a closed anaerobic tank system including gas engines for electricity production from the produced biogas are estimated at 19 million Baht (or 10,000 Baht/m^3 of wastewater per day). The pay back time for this system, when calculating the saved electricity as an income, is thus about 4.3 years.

3.5.2. *A physical – technological model of the industrial ecosystem with minimum waste*

The environmentally sustainable optimum in waste minimization involves a system in which minimal waste streams are discharged into the air or water, or onto the land and the costs of the system to achieve the suitable discharges are acceptable. These goals are achieved by reuse or recycling of the waste materials of one plant as the raw material input for another with a minimum of transport. A key challenge for environmental improvement is therefore the development of industrial ecosystems emphasizing the relations between companies in an effort to create direct exchanges of wastes and by-products between different industrial processes. This way the total amount of waste that goes to final disposal is reduced. The case-studies and the literature review showed that there are interesting opportunities for the use of waste/by-products from crude palm oil production in other industries and in agriculture. This section presents the most interesting clean technology and waste exchange options available for palm oil mills in order to contribute to the objective of creating a 'zero waste discharge plant.'

Based on the analysis of the existing material and energy flows at the five selected crude palm oil mills, a model of an almost zero waste industrial ecosystem for crude palm oil industry will be given. Figure 7 presents a schematic diagram of such a crude palm oil mill with an environmentally balanced industrial complex. The estimated mass balances given in this figure are based on the extraction of 1000 ton of fresh fruit bunches, resulting in the generation of about 640 m^3 of wastewater, 240 tons of empty fruit bunches, 140 tons of fiber, 60 tons of shell and 42 tons of sludge from decanter.

It is clear that EFB and wastewater from the crude palm oil mill contain high K, N, P and Mg levels and can be used as a fertilizer in the oil palm plantation area. From a calculation based on the extraction of 300,000 tons of FFB/year, it can be concluded that the nutrients contents in EFB are equal to 402, 30, 1230 and 90 ton of N, P, K and Mg, respectively. For wastewater, the quantities of N, P, K and Mg are equal to 64.3, 5.3, 37.8 and 37.8 tons/year, respectively. These residues are to be used to replace a portion of a chemical fertilizer needed in the plantation area to grow oil palms.

The total amount of waste that can be used as fertilizer to replace (a part of) the commercial fertilizer needed in the plantation area is shown in Table VI. Since the

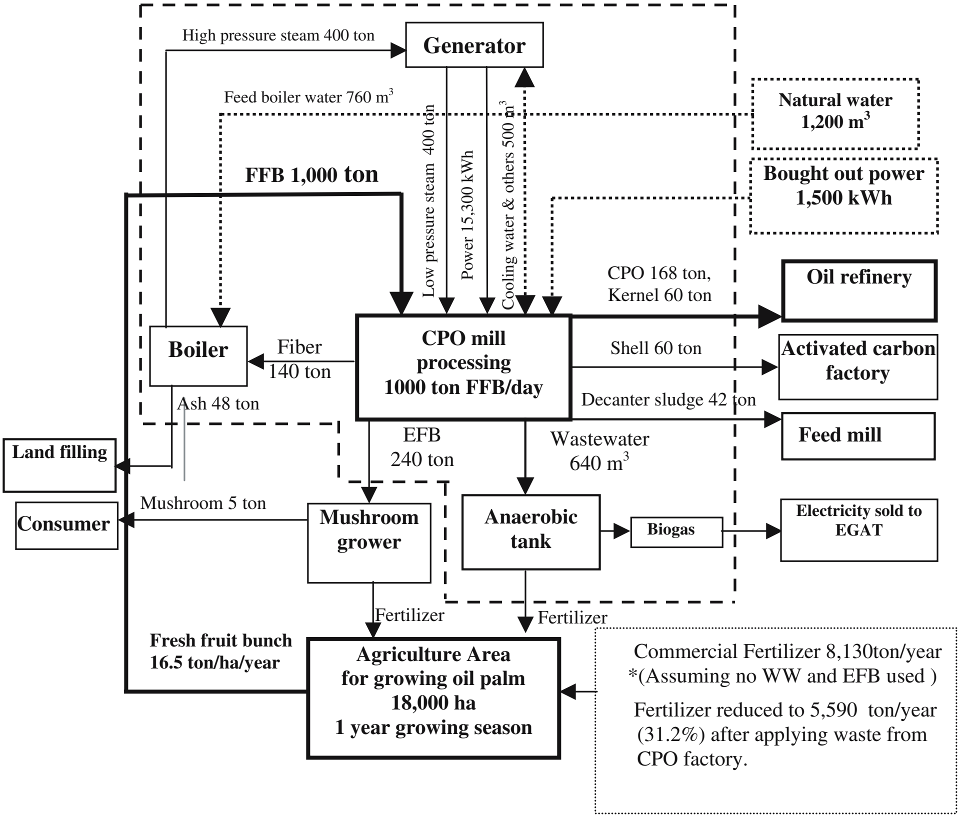

Figure 7. Material balance of the proposed physical–technological model of a CPO industrial ecosystem with a minimum waste. ▬▬, Production line; – –, Boundary of CPO; ·······, Factory; ——, Natural resource input; ▪▪▪▪▪, Product/by-product/waste.

EFB and wastewater may not contain all the required types and quantities of nutrients comparable to a commercial fertilizer on a unit – weight basis, an appropriate amount of commercial fertilizer should be applied to the palm oil plantation area to meet the necessary growth requirements, depending on the age of the oil palm trees. Approximately 18,000 ha of land are required for an annual harvest of 300,000 ton of FFB as stock for extraction at a rate of 1000 ton/day.

TABLE VI. Balance of fertilizer demand for oil palm plantation area.

Fertilizer demand	N	P	K	Mg	B
Old palm tree (kg/ha/year)	204	26.3	70	26.3	12.5
Oil palm tree (tons/18,000 ha/year)	4890	630	1680	630	300
Fertilizer from waste (EFB & WW) (ton/year)	466	35	1268	468	–
Commercial fertilizer (ton/year)	4424	595	412	162	300
Reduce commercial fertilizer (%)	9.5	5.6	75.4	74.3	0

4. Conclusion

Crude palm oil mills generate many by-products and large quantities of wastewater, which may have a significant impact on the environment if they are not managed properly. An industrial ecosystem approach for the crude palm oil industry, based on reuse, recycling, and utilization of solid and liquid waste and appropriate energy management, can achieve the goal of almost zero discharge of pollutants (against acceptable costs). Such an approach can contribute in transforming the palm oil mill into a more environmentally friendly industrial activity.

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