

CHAPTER 3

METHODOLOGIES

3.1 Phase I: LCA of biofuel systems in Thailand

3.1.1 Goal and scope definition

In this study, life cycle assessment (LCA) of cassava ethanol, molasses ethanol and palm biodiesel are performed to identify environmental aspects of the existing ethanol production system in Thailand. The analysed results focus on (1) the identification of current significant environmental risks and (2) recommendations in order to improve the environmental performance of biofuels production in Thailand. The scope of the study is “cradle to gate” including cultivation and harvesting of feedstocks, feedstocks transport, feedstocks processing, biofuel conversion, by-products processing and on-site waste management (**Figure 3.1**). The reference flow of the study is producing 1000 L of bio-ethanol and biodiesel. Inventory analysis centers on resources used, land occupied, atmospheric emissions and water emissions. The crucial emissions that were estimated include the atmospheric emissions i.e. CO₂, NO_x, SO_x, CH₄, N₂O and the waterborne emissions i.e. COD, BOD, Total P, Total N and suspended solids. These are primary parameters associated with the key environmental impacts of biofuels.

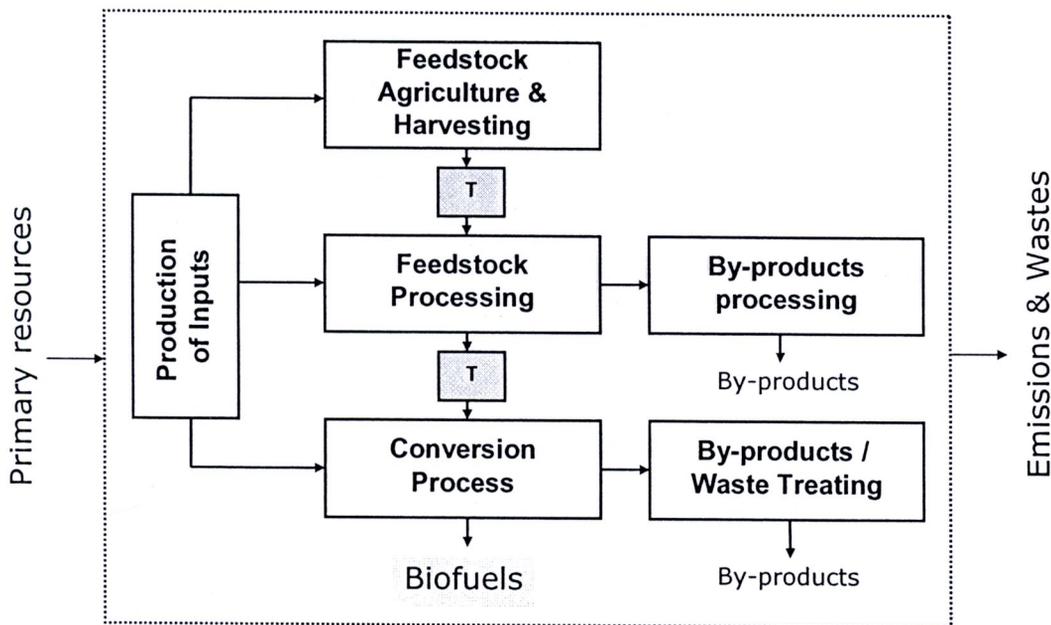


Figure 3.1 Simplified biofuel system

For the life cycle impact assessment (LCIA) step, the CML 2 method is used [82-83]. This methodology follows the problem oriented (mid-point) approach where environmental burdens are aggregated according to their relative contribution to the environmental effects that they might cause [83]. For instance, the different greenhouse gases are aggregated to evaluate the global warming potential (presented in CO₂ equivalents), not the damage caused by climate change. Analysis at the mid-point level is an effective approach to LCIA in that its results have scientific reliability and reduce the complexity of modeling by minimizing the amount of forecasting and effect modeling [24]. The potential environmental impacts categories selected for this study include land use, global warming, photochemical oxidation, acidification and eutrophication which related to the environmental emissions identified in this study.

3.1.2 Data sources

The data for this assessment are mainly based on on-site investigations, a large amount of data, such as data related to fertilizers, herbicides, seed stems, etc. during plantation, transportation distance, type of fuels used in ethanol conversion process, are obtained from the factories. Some data are from publications and Thailand statistical records. The summaries of data sources for performing LCA of cassava ethanol, molasses ethanol and palm biodiesel in Thailand are shown in **Table 3.1 – 3.3**, respectively. Energy values for NEB analyses are shown in Appendix A.

Table 3.1 Data sources for performing LCA of cassava ethanol production in Thailand

Life cycle stage	Data requirements	Data sources	Data processing
Cassava farming	Diesel use, Fertilizers use Herbicides use	[84]	Energy use - Energy content of fuels ^a : [86] - Input efficiency coefficients: [87] - Fertilizers manuf.: [88] - Herbicides manuf.: [89-90] - Electricity ^b : [86] - Labour: [85]
	Labour use	[85]	
	Yield	[91]	
Cassava drying floors	Fuel use	Primary data from drying floors [19]	
	Dried chips yield	[91]	
Ethanol conversion	Production capacity Fuel use Biogas recovery	Primary data from cassava ethanol plant [84]	Emissions - Diesel and coal manuf.: [92], - Grid-mix electricity production ^b : [93] - Fertilizers and herbicides manuf.: [90-91]
Transportation	Mode, Capacity and Distance	Primary data from cassava ethanol plant [84]	- Fertilizer application (N ₂ O emissions): [94] - Stack gases emissions from boilers in ethanol plant [84]

^aPrimary energy of diesel and coal were estimated by using fuel energy contents divided by input efficiency coefficients.

^bFor grid-mix electricity, the factor 10 was used to convert one kWh_e to primary energy based on the overall efficiency of power production in Thailand [95].

Table 3.2 Data sources for performing LCA of molasses ethanol production in Thailand

Life cycle stage	Data requirements	Data sources	Data processing
Sugarcane farming	Diesel use, Fertilizers use Herbicides use	[84]	Energy use - Energy content of fuels ^a : [86] - Input efficiency coefficients: [87] - Fertilizers manuf.: [88] - Herbicides manuf.: [89-90] - Rice husk, bagasses, corn cob: [86] - Labour: [21]
	Labour use	[21]	
	Yield	[91]	
	Cane trash utilization & burning	[84]	
Sugar/Molasses production	Production capacity Fuel use Surplus electricity sold to grid	Production data from 3 sugar mills [84]	
Ethanol conversion	Production capacity Fuel use Spentwash treatment/ utilization	Primary data from three molasses ethanol plants [84]	Emissions - Diesel manuf.: [92] - Grid-mix electricity production ^b : [93] - Fertilizers and herbicides manuf.: [89-90] - Fertilizer application (N ₂ O emissions): [94].
Transportation	Mode, Capacity and Distance	Primary data from three molasses ethanol plants [84]	- Stack gases emissions from boilers in sugar and ethanol plants: Primary data from 3 sugar millings and 3 ethanol plants [84] - Emissions from cane trash burning: [96] - Emissions from transport: [92]

Table 3.3 Data sources for performing LCA of palm biodiesel production in Thailand

Life cycle stage	Data requirements	Data sources	Data processing
Oil palm plantation	Material used	[97]	Energy use - Energy content of fuels ^a : [86] - Input efficiency coefficients: [87] - Fertilizers manuf.: [88] - Herbicides manuf.: [89-90] - Methanol manuf.: [101] - NaOH manuf.: [102] - Electricity ^b : [95]
	Yield	[99]	
Palm oil milling	FFB and other material inputs, energy used, crude palm oil produced, by-products generated and stack gas emissions	[97, 100]	
Biodiesel production	CPO and other material inputs, energy used and PME and glycerol produced	[97]	Emissions - Diesel manuf.: [92] - Grid-mix electricity production ^b : [93] - Fertilizers manuf.: [103] - Herbicides manuf.: [101] - Methanol manuf.: [101] - NaOH manuf.: [102] - Fertilizer application (N ₂ O emissions): [94] - Emissions from transport: [92] - Crude oil extraction: [92]
Transportation	Truck: Load, diesel used and emissions per ton.km	[92]	
	Trailer: Load, diesel used and emissions per ton.km	[92]	
	Distance (round trip)	[97]	

3.1.3 Cassava ethanol system

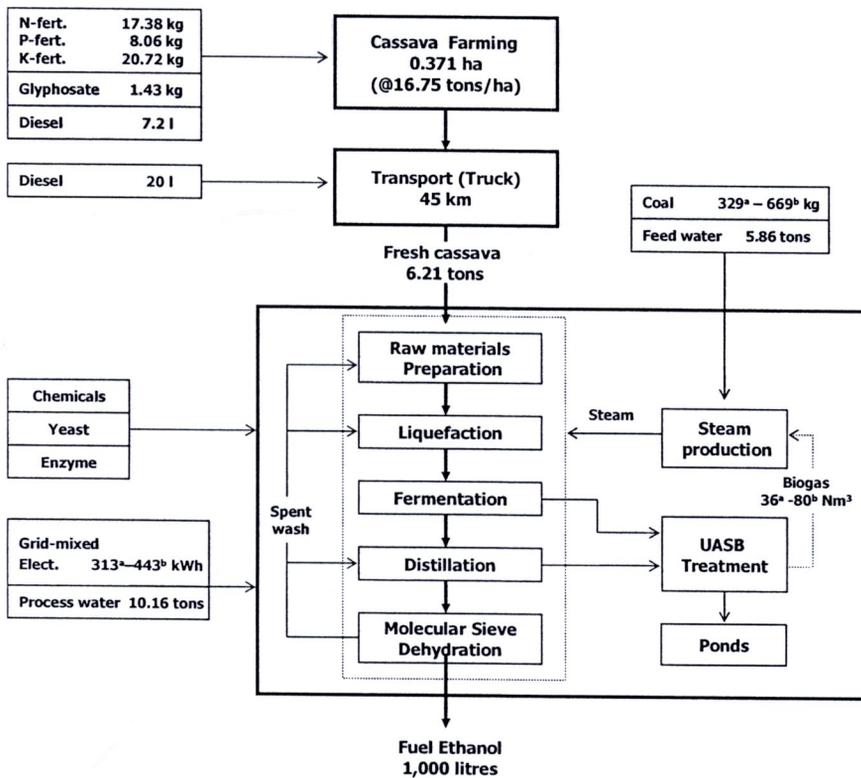
The “cradle to gate” of the cassava ethanol system consists of four stages including (1) cassava cultivation and harvesting, (2) fresh cassava transport (3) cassava processing and (4) ethanol conversion. The details of each stage are described below:

a. Cassava cultivation and harvesting: This stage consists of land preparation, stake preparation, planting, treatment and harvesting. Referring to the data sources shown in **Table 3.1**, an average fresh cassava yield about 2.68 tonnes fresh cassava/rai [1 rai = 0.16 hectare] or 16.75 tonnes fresh cassava/ha was used in the study. The amount of N-P-K fertilizers and fuel used for the cultivation and harvesting stages are shown in Fig. 1. The amount of fresh cassava consumed for producing 1000 L of ethanol (99.5% purity) is 6.12 tonnes. Manual planting is a common practice in Thailand. The total labour works of 442 Man-hours per hectare of cassava are accounted since land preparation to harvesting [85]. Even though, there were many methods for evaluating the energy equivalent from human work inputs and many researchers have used different values range 0.62 – 12.1 MJ/person/hr ([85, 104-106]. However, one of the most popular methods is “Total Food Consumed (TFC)” which is applied in this analysis [18, 85, 104-105]. Regarding TFC method, the value of 2.3 MJ/h derived for human labour energy equivalent was obtained and used to convert hours of labour to energy.

b. Transport: The fresh cassava roots are directly transported from the main suppliers or local farmers to the ethanol plant by truck or pick-up car. In general, fresh cassava is transported to drying floors which are equipped with simple facilities in order to make the dry chips. The previous research on environmental assessment of a pilot plant at the Cassava and Starch Technology Research Unit (CSTRU), Kasetsart University (KU) was based on dry cassava chips as the main raw material [19, 107]. However, the existing full scale plant on which this study is based uses fresh cassava as the main raw material, while dry cassava chips are reserved in case of fresh cassava shortage. Therefore, very less amount of dry cassava chips are supplied to this ethanol plant.

c. Ethanol conversion: The cassava-ethanol plant consists of four main sub-processes: milling, mixing and liquefaction, fermentation, distillation and molecular sieve dehydration. In this stage, environmental impacts related to several aspects, such as emissions from combustion of fuel in industrial boilers for steam production, emissions from electric power used in the plant and water emissions after treatment by the Upflow Anaerobic Sludge Blanket (UASB) system were accounted. From the UASB, biogas is a by-product that is used as fuel for steam production, CO₂ emissions from biogas combustion, being of biogenic origin, are considered net zero as also the bio-based CO₂

emissions during fermentation. Direct material and energy flows associated with fuel ethanol from cassava are shown in **Figure 3.2**.



Remark: ^aScenario I: Current Operation

^bScenario II: Designed Operation

Figure 3.2 Life cycle materials flow diagram of cassava based ethanol

3.1.4 Molasses Ethanol System

The “cradle to gate” of molasses based ethanol system in this study consists of four stages including (1) sugar cane farming and harvesting, (2) sugar milling (3) ethanol conversion and (4) transportation during each stage. The details are presented below:

a. Sugar cane farming and harvesting: Sugarcane farming includes field preparation, plant cane farming, treatment and harvesting. Sugar cane is initially grown from short sections of cane (plant cane). For the next three years the cane is cut and regrown (ratoon cane) before replanting with new cane stems. A cycle of sugarcane planting and harvesting is about 12 months. The average sugarcane yield from four cycles is 9.65 tonnes.ra⁻¹.yr⁻¹ (60.31 tonnes.ha⁻¹.yr⁻¹) based on the decreasing rate of sugarcane yield [84]. Fertilizers and diesel used for cultivation and harvesting of sugarcane are 78

kg.rai⁻¹ (487.5 kg.ha⁻¹) and 35.78 L.rai⁻¹ (223.6 L.ha⁻¹) respectively. An average human labour of 466 man-hours per hectare of sugarcane is required for all farming activities since land preparation, planting, crop maintenance and harvesting [21].

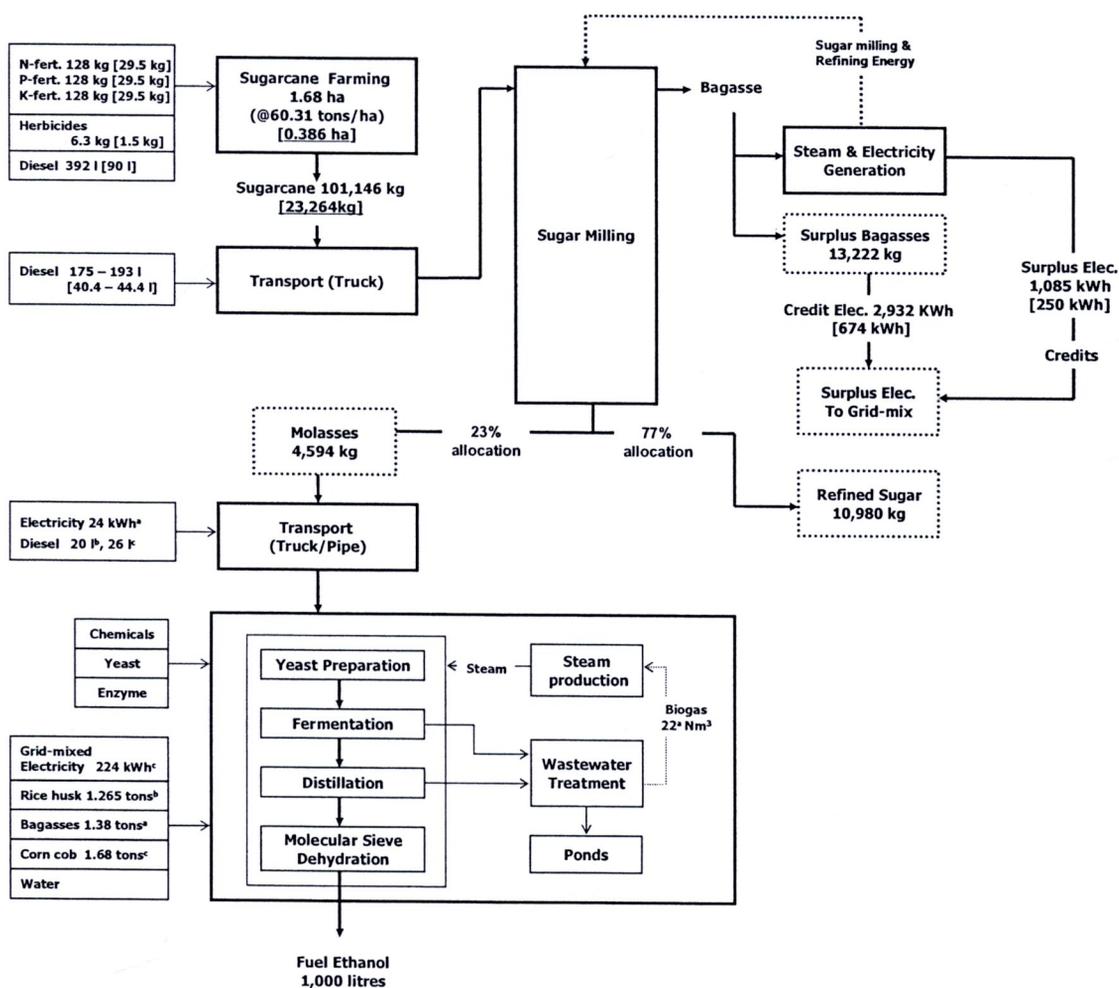
b. Sugar milling: Sugar milling involves crushing cane to extract sugar juice. This juice is clarified to remove any impurities and concentrated into syrup by boiling off excess water, seeded with raw sugar crystals in a vacuum pan and boiled until sugar crystals have formed and grown. The crystals are separated from the syrup by centrifugal process before more crystals are grown in the syrup. Molasses is the syrup remaining after the sugar has passed through the centrifuge for the last time in a mill or refinery. Products and by-products of sugar milling include raw sugar, refined sugar, super refined sugar, molasses and bagasse. Bagasse is used to produce steam and electricity. The surplus electricity is sold to the general grid-mix and can thus get the credits from avoided conventional electricity production.

Molasses is an internationally traded commodity with total sugar content as the key quality criterion. This sugar content in the molasses will be converted to ethanol in the fermentation process. Therefore, the energy content of the molasses and sugar products will be different depending on the total sugar content in each product. Energy based allocation technique was applied to share the environmental burdens from sugarcane cultivation and sugar mill between the co-products, sugar and molasses. To determine the allocation factor, all kinds of sugar products have been assumed to have an average energy content ($HV_{\text{sugar}} = 16.33 \text{ MJ/kg}$) and the energy content of molasses is ($HV_{\text{molasses}} = 11.43 \text{ MJ/kg}$) [84]. Allocation factor for molasses (AF_{molasses}) can be calculated from $AF_{\text{molasses}} = (M_{\text{molasses}} \times HV_{\text{molasses}}) / (\sum M_{\text{sugar},i} \times HV_{\text{sugar}} + M_{\text{molasses}} \times HV_{\text{molasses}})$, where $M_{\text{sugar},i}$ is the mass of sugar product (i) and M_{molasses} the mass of molasses per ton sugarcane. The above calculations yielded a factor of 0.23 which was used to determine the environmental burdens from molasses production.

c. Ethanol conversion: The process of making molasses based ethanol consists of yeast preparation, fermentation, distillation and dehydration. This study refers to the production data from three ethanol producers and the product is 99.5% purity ethanol for using in gasohol. The generation of bio-based CO₂ from fermentation was not accounted for in the life cycle assessment.

d. Transport: The whole cycle of molasses ethanol production involves transportation of sugarcane to the sugar mill and transportation of molasses to the ethanol

plant. Sugarcane can be transported to the sugar mill by various types of trucks e.g. 15-t truck, 21-t truck, or trailer. The average distance (one-way trip) of 10 sugar mills in Thailand is 42.5 km. The most widely used truck for transporting sugarcane ranges between 18 to 25 tonnes per trip (average value used in the study is 21.50 tonnes per trip) [84]. Trucks are generally used for transporting molasses to the commercial ethanol manufacturers; however, some molasses ethanol plants receive molasses from the sugar mills through pipeline. This study assumes that 140 km (102-206 km) is the average road distance (from four molasses ethanol producers) for transporting molasses to the ethanol plant [84]. Direct material and energy flows associated with the molasses-ethanol cycle are shown in **Figure 3.3**.



Remark: [] values in parentheses are the results after allocation to molasses. .

^aSpecific inputs for the MoE Plant-1; ^bSpecific inputs for the MoE Plant-2; ^cSpecific inputs for the MoE Plant-3

Figure 3.3 Life cycle materials flow diagram of molasses based ethanol

3.1.5 Palm oil Biodiesel System

The production of biodiesel from CPO for Transport in Thailand is composed of several stages including (1) planting of oil palm, (2) CPO production, (3) biodiesel production, (4) blending of biodiesel with diesel fuel (5) all transportation activities. The overall biodiesel production system is described below for each step.

a. Oil palm cultivation: This step consists of 2 stages, growing at the nursery and planting in the field. . The nursery includes pre- and main-nursery. In the pre-nursery, the sowing of seed in a small poly bags until seedling is approximately three to four months. After that, in the main-nursery, the seedling is planted in a larger policy bag until it is 12 to 13 months old and ready for planting. Oil palm start bearing bunches 2.5 – 3 years after field planting. The first harvest is possible after five years, and the plant lifetime is around 25 years before replanting again. The frequency of a harvesting is around 10-15 days or 2-3 times a month. The plantation has 21-22 tress per rai. The average the fresh fruit bunches (FFB) yield in Thailand is 2.8 tonnes.raⁱ.yr⁻¹ (17.5 tonnes.ha⁻¹.yr⁻¹) [99]. The seeds of oil palm are applied at 26.9 kg.raⁱ. The applied fertilizers are 24.2 kg.raⁱ.yr⁻¹ for N-fertilizer, 11.5 kg.raⁱ.yr⁻¹ for P₂O₅-fertilizers and 49.1 kg.raⁱ.yr⁻¹ for K₂O-fertilizer. Herbicides such as glyphosate and paraquat which used as herbicides are applied at 0.76 and 0.26 kg.raⁱ.yr⁻¹, respectively. While most of the harvest is done manually, some machinery, farm equipment, and trucks for FFB transport require fossil energy. Diesel consumption for field operation is around 1 litre.raⁱ.yr⁻¹.

b. CPO production: This stage consists of several processing steps and a number of by-products and waste generated including: Loading of FFB in the mill; Sterilization of FFB; Bunch stripping – the empty fruit bunches (EFB) separated from the fruits are conventionally treated by dumping or mulching in plantation. However, they can also be managed in the other ways such as being used as biomass fuel for in-house steam and power generation, or together with palm oil mill effluent (POME) for co-composting or utilization as substrate for straw mushroom cultivation; Digestion of separated fruits; Crude palm oil extraction from oil mash and separation of decanter cake; Nut/fiber separation – fiber is used a fuel for boiler house to produce steam and electricity in the palm oil processing mill itself; Nut cracking – kernels and shell are separated at this stage. Palm kernel oil (PKO) and palm kernel extract (PKE) are produced from the mechanical processing of kernels while the separated shells are partially be used as fuel in boiler. The

remaining shells can be sold as solid fuel or sold as material for producing activated carbon. The selling price of shells is around 1.5 – 2.3 THB/kg [108].

Based on average data from five palm oil mills in Thailand of Chavalparit (2006), to produce a kilogram of CPO, 5.95 kg of FFB are required. In addition, by-products and waste materials generated include fiber, shell, kernel, decanter cake and empty fruit bunches (EFB) at about 0.83, 0.36, 0.45 and 1.43 kg, respectively. Economic based allocation technique was applied to share the environmental burdens from oil palm cultivation and palm oil mill between the main product i.e. crude palm oil (CPO) and the co-products that are sold as raw material or fuel i.e. palm kernel and shell. To determine the allocation factors, the average prices of CPO (P_{CPO}), palm kernel (P_{kernel}) and shell (P_{shell}) are 23 THB/kg [99], 14 THB/kg and 2 THB/kg [108], respectively have been used. Allocation factor for CPO (AF_{CPO}) can be calculated from $AF_{CPO} = (Q_{CPO} \times P_{CPO}) / (Q_{CPO} \times P_{CPO} + Q_{kernel} \times P_{kernel} + Q_{shell} \times P_{shell})$, where Q_{CPO} is the amount of CPO; Q_{kernel} is the amount of kernel per ton FFB; and Q_{shell} is the amount of shell per ton FFB. The above calculations yield a factor of 0.81 which is used to determine the environmental burdens from CPO production. Allocation is not required for the fiber and a part of shells that are used as fuel for in-house steam and power generation; this can be considered an internal recycling. EFB and decanter cake which currently have no use but are actually dumped by some mills at the oil palm plantations, are primarily considered in this base case as waste and hence no environmental burdens are allocated to them. Details of the CPO production system are shown in **Figure 3.4**. CPO is processed further for biodiesel production and palm kernels are used for crude palm kernel oil (C_{PKO}) production.

c. Biodiesel production: At the biodiesel plant, CPO is transesterified with the help of a catalyst, sodium hydroxide (NaOH), and methanol. At this stage, the inputs are CPO, water, electricity, methanol and sodium hydroxide. Outputs from the process include palm methyl ester (biodiesel), glycerol and wastewater. Economic allocation is also share the environmental burdens between biodiesel and glycerol. The market values of PME and glycerol are 32 THB/L [111] and 18 THB/kg [112], respectively. The allocation factors obtained are 0.92 for PME and 0.08 for glycerol.

d. Transport: Transport of FFB from field to mills and transport of CPO from mills to biodiesel plant are considered. Usually the small farmers sell their product to middlemen, who operate the ramp and deal with different mills in terms of delivered

volume and prices. This leads to a situation where not always the shortest distance is chosen for the next mill. Transport capacity and distance traveled from field to mills (56 km round trip) and mills to biodiesel plant (422 km for round-trip) are retrieved from [97].

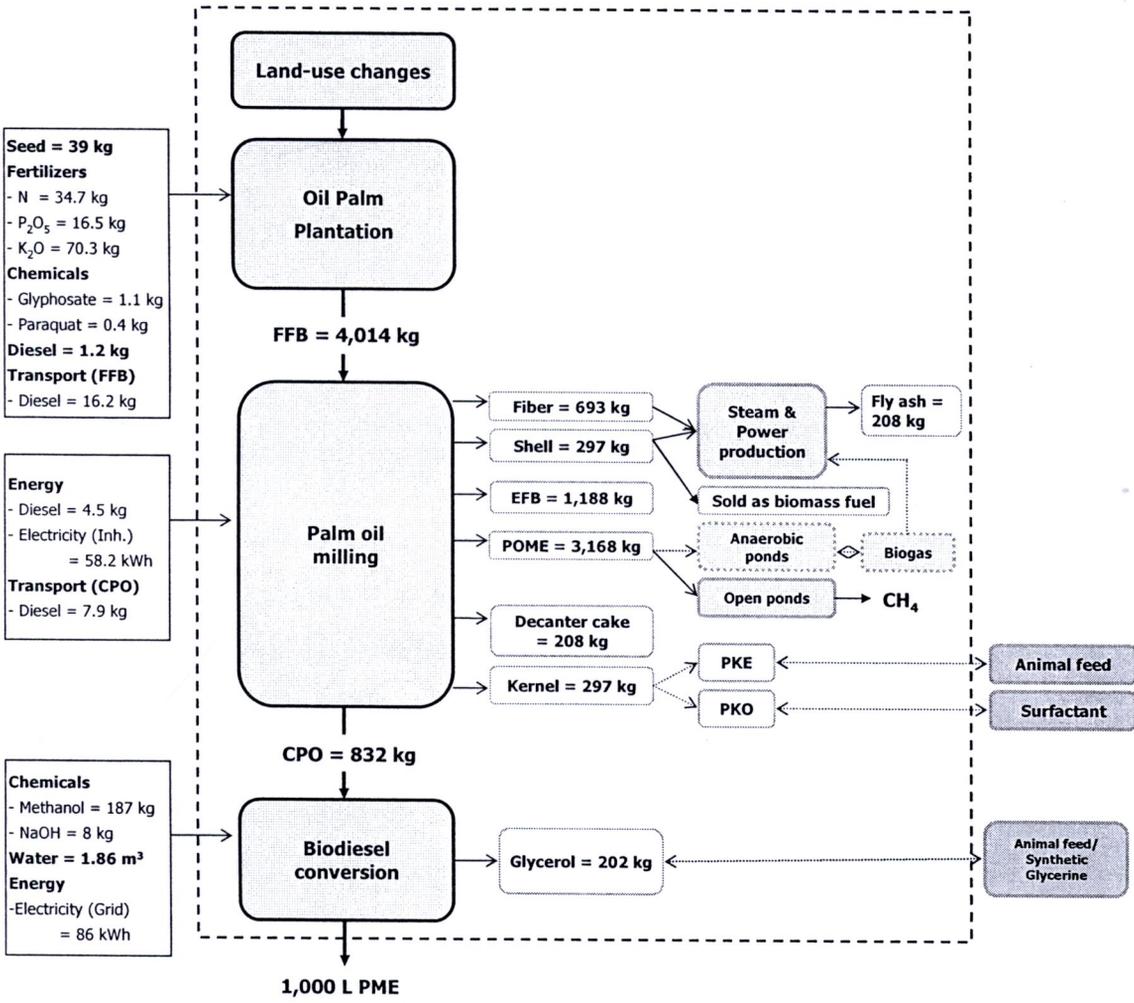


Figure 3.4 Life cycle materials flow diagram of palm oil biodiesel

Apart from the main processes described above, steam generation from the mills is also an important process which contributes to emissions of stack gases. In the process of palm oil milling, a huge amount of POME, wastewater which originated from the fruit itself and some added fresh water during the milling steps, containing around 700-1200 mg/L COD and pH ranging between 4 and 5, is treated in different ways depending on the mills [109]. Direct discharge of POME to the environment is not allowed due to high organic loading, therefore, some mills collect it in open ponds and leave it there for self-purification. Others use anaerobic digestion system for treatment and the treated POME is applied for irrigation. However, of late, the biogas production from POME has gained

attention in Thailand due to the enhancement by the Clean Development Mechanism (CDM) opportunities. During anaerobic treatment, biogas with a composition of approximately 60% CH₄ and 40% CO₂ can be generated [109-110]. This CO₂ from biogas can be considered carbon neutral as the amount of carbon released is the same amount of carbon that had been sequestered during the growth of FFB. However, CH₄ emission cannot be considered neutral in terms of GHG emission as it has a higher GWP than the CO₂ that was taken up by FFB.

3.2 Phase II: LCC and Externalities of Biofuels in Thailand

3.2.1 Goal and scope definition

This phase of dissertation aims to determine the influence of externalities on the cost performance of biofuels in Thailand. Life cycle cost (LCC) and preliminary assessment of externalities of biofuels are performed to determine that whether bioethanol and biodiesel in Thailand can compete with petroleum fuels such gasoline and diesel if the environmental externalities were internalized into their total production cost. The obtained results would provide valuable information to policy makers in their move towards the promotion of biofuels in the transport sector. To perform the assessment, a LCC is conducted with the same system specification as in LCA as in **Section 3.1** but indicating the cost of 1 km distance driven. The additional two life cycle stages i.e. blending and use of biofuels blended in vehicles are included into the system boundary. The general formula of full life cycle cost of biofuels in this analysis is as follows:

$$FLCC_{biofuel} = LCC_{biofuel} + EC_{biofuel}$$

where $FLCC_{biofuel}$ is the full life cycle cost of biofuels (THB/km); $LCC_{biofuel}$ is the life cycle cost of biofuel (THB/km); $EC_{biofuel}$ is the external costs of biofuels (THB/km).

3.2.1.1 Scope of LCC comparison between bioethanol and gasoline

The cost performance comparison between bioethanol and gasoline is divided into two sections. The first section is a comparison in terms of ex-refinery price per litre of gasoline equivalent by assuming that 1 litre of ethanol produces the same performance as 0.65 litre of gasoline [34, 113]. This factor comes from the ratio of the different calorific values of bio-ethanol (21.2 MJ per litre) and conventional gasoline (32.4 MJ per litre). The second section is the comparison by determining the substitution ratio between ethanol and

gasoline based on the real fuel economy in a motor vehicle engine [19, 114]. For instance, the PTT Research and Technology Institute, has performed test of various car models running on CG (ULG95) and gasohol E10. The results based on Toyota 1.6L/2000, the newest car model in the test groups, show that the fuel economy of this car model running on CG and Gasohol is 13.46 km per litre and 13.31 km per litre, respectively. Fuel economy comparison reveals that 1 L of gasohol is equal to 0.989 L of CG. The difference of 0.011 L is due to 10% of ethanol in CG. The substitution ratio between ethanol (in E10 form) and CG in a motor vehicle engine is therefore 1:0.89 based on fuel economy, instead of 1:0.65 based on energy content. Choosing the substitution ratio derived from fuel economy links directly to the emissions of air pollutants generated during the combustion of biofuel in a car engine and therefore to the direct determination of the resulting environmental externalities (distance travelled by a vehicle, e.g. kg CO₂/km driven). Based on this method, the substitution ratios between E20 and E85 and E100 with CG in a motor vehicle engine are 0.78 and 0.67, respectively (as **Table 3.4**).

Table 3.4 Fuel economy for gasohol and gasoline

Testing results	Fuel economy (km/litre)	Substitution ratio between ethanol (in gasohol forms) and gasoline	Source
Gasoline E10	13.46 13.31	Ethanol: GSL (in E10 form) = 1:0.89	[114]
Gasoline E20	13.19 12.61	Ethanol: GSL (in E20 form) = 1:0.78	[115]
Gasoline E85	13.26 9.51	Ethanol: GSL (in E85 form) = 1:0.67	[116-117]

3.2.1.2 Scope of LCC comparison between biodiesel and diesel

In this study, the exhaust emissions (g/km) and fuel economy (km/l) of different types of biodiesel blends refer to tests which were conducted at the Automotive Emission Laboratory of the Pollution Control Department in Thailand [108]. The tests were running on chassis dynamometer under identical driving cycles. The emission values are dependent on the engine technology employed and testing conditions as shown in **Table 3.5**. The comparison indicates marginal reductions in carbon monoxide (CO), hydrocarbon (HC) and particulate matter (PM) emissions from vehicles using various biodiesel blends instead of diesel. For biodiesel, emissions of oxides of nitrogen (NO_x) were slightly higher, while the carbon dioxide (CO₂) emissions from all biodiesel blends were higher than that of diesel. According to the US Department of Agriculture and US Department of Energy

(1998), this is due to a more complete combustion (in vehicle engine) of conventional diesel fuel which is also accompanied by a concomitant reduction in other carbon-containing tailpipe emissions [118]. However, the use of biodiesel in vehicles is generally considered carbon neutral. The carbon atoms from fossil methanol still contribute to atmospheric emissions. The amount of these emissions is determined by assuming that one carbon atom in the empirical formula of PME ($C_{18}H_{35}O_2$) has its origin in fossil methanol [119-120].

Table 3.5 Exhaust emissions and fuel economy for vehicles using various biodiesel blends and diesel [108]

Testing Conditions LDDV(2,835 cc., model 2002); Driving Cycles: BKK; Date: 02/06/2007 to 03/03/2007						
	Fuel economy (km/litre)	CO ₂ (g/km)	CO (g/km)	NO _x (g/km)	THC (g/km)	PM (g/km)
Diesel	11.74	224.861	0.137	1.644	0.009	0.075
B2	11.47	230.336	0.125	1.608	0.01	0.072
B5	11.92	233.349	0.119	1.633	0.011	0.072
B10	12.33	225.126	0.142	1.619	0.011	0.071
B100	11.96	232.482	0.143	1.789	0.01	0.035

3.2.2 Life cycle cost calculation

Life cycle cost of biofuel is the sum of all the costs arising from the biofuels system i.e. since feedstock cultivation, feedstock processing, biofuel conversion and all transport activities. The basic formula for LCC calculation in the study is as follows:

$$LCC_{biofuel} = C_{Feedstock} + C_{Conv} + C_T + C_I - C_{BP}$$

where $LCC_{biofuel}$ is the biofuels production cost (THB/L); $C_{Feedstock}$ is the feedstock cost (THB/L); C_{Conv} is the conversion costs of biofuels (THB/L) which include operation, maintenance, fuel, waste treatment cost, salary and etc.; C_T is the transportation cost of biofuels (THB/L); C_I is the investment cost (THB/L) and C_{BP} is the by-product gains (THB/L). Nevertheless, in this calculation, C_T in the formula will represent to the transport cost from biofuel factory to blending site only. This is because the costs in other transport activities have been already included in the prices of raw material input. Meanwhile, C_I of biofuel plant is neglected as it has already included in the conversion cost of biofuels (in terms of depreciation cost).

3.2.3 Externalities/ Environmental cost estimations

Mitigation of GHG emissions is one of the environmental benefits usually referred to for promoting biofuels. However, the benefit of CO₂ abatement during the combustion of biofuels must also be paid by other environmental impacts such as reduced biodiversity and increased GHG emissions due to land conversion for biofuel crops. Moreover, the net GHG balance can be negative because producing biofuels may require much more energy than fossil fuel when considering all the downstream processes. Therefore, the environmental burdens including land use, fossil fuel consumption, air pollutants emissions i.e. CO₂, CH₄, N₂O, CO, NO_x, SO₂, VOC and PM₁₀, for biofuels and petroleum fuels will be accounted for in order to determine the total environmental costs. To perform a reliable external costs assessment of biofuels will help support policy decision makers to focus on following issues, i.e. internalisation of the external costs of energy, optimization of site selection processes, cost benefit analysis of abatement measures and comparative assessment of biofuel systems.

Benefit transfer is one of the methodologies that can be used to value the non-market environmental commodities. With this method, the economic information gathered from one place and time is used to make inference about the economic values of environmental commodities in another place and time [121]. To carry out the benefit transfer, the most common approaches can be either transferred as monetary value units of unadjusted mean willingness to pay (WTP) (namely “mean value transfers”) or as value functions conditioned on explanatory variables that define the attributes of an ecological and economic choice setting (or namely “value function transfers) [121-122].

In this study the environmental values from the Environmental Priority Strategies in product design version 2000 [39], a life cycle impact assessment method developed by the Centre for the Environmental Assessment of Products and Material systems (CPM), Sweden, was used and adjusted to the Thai context using an appropriate multiplier factor, namely, the income elasticity of willingness to pay (WTP). A crucial hypothesis in making such adjustments is that WTP to avoid damages is proportional to the per capita income [123-125]. The equation that was used to estimate WTP for Thailand is shown below:

$$WTP_{Thailand} = \frac{WTP_{EU} \times Percap - GDP(PPP)_{Thailand}}{Percap - GDP(PPP)_{EU}}$$

where GDP per capita (PPP) in Thailand $Percap - GDP(PPP)_{Thailand} = \text{US\$ } 8,000$ [126] and GDP per capita (PPP) in European countries $Percap - GDP(PPP)_{EU} = \text{US\$ } 32,700$ [126]. The income elasticity of WTP—the percentage change in WTP corresponding to a one percent change in the income was assumed to be equal to unity. **Table 3.6** presents the environmental costs for Thailand that were calculated from the values of WTP (for European countries) reported in EPS 2000.

Table 3.6 Environmental costs per units of burdens

Environmental categories	Units	Adjusted external cost (THB per unit) ²
Land use	rai ¹ .yr	29.11
Fossil fuel		
<i>Petroleum use</i>	<i>MJ (energy-oil)</i>	<i>0.15</i>
<i>Coal use</i>	<i>MJ (energy-coal)</i>	<i>0.02</i>
Air pollution		
<i>CO₂</i>	kg CO ₂	1.28
<i>CH₄</i>	kg CH ₄	31.68
<i>N₂O</i>	kg N ₂ O	446.11
<i>CO</i>	kg CO	3.84
<i>NO_x</i>	kg NO _x	24.81
<i>SO₂</i>	kg SO ₂	38.09
<i>VOC</i>	kg VOC	24.93
<i>PM₁₀</i>	kg PM ₁₀	420.02

¹ [1 rai = 0.16 hectare]

² Based on the exchange rate 47.6 THB.EUR⁻¹ (www.xrate.com)

The general formula for determine the external cost of biofuel in this study can be summarized as follows:

$$EC_{biofuel} = \sum_i EC_i \times LCI_{biofuel,i}$$

where $EC_{biofuel}$ = external cost of biofuel (THB/L biofuel); EC_i = external cost per unit of environmental category i (THB/unit of environmental category i); and $LCI_{biofuel,i}$ = life cycle inventory of the environmental category i of biofuel (unit of environmental category i /L biofuel)

3.3 Phase III: Feedstocks availability assessment

This phase aims to assess the long-term security of feedstock supply to satisfy the increased demand for biofuels production in Thailand according to the government policy

targets. The goals and policies in the recent 15 years biofuels development plan (2008–2022) are used to model the long-term bio-ethanol system in Thailand [9]. Key distinguished dimensions related to security of supply including the availability and the diversity of feedstock to supply for the future Thai biofuels system are investigated by using Net feedstock balances and Shannon Index. Descriptions for those indicators are shown below.

3.3.1 Feedstock resource estimates and Net feedstock balances

Feedstock resource estimates and the Net feedstock balances are referred as the indicators to describe the physical availability of feedstocks to supply for long-term bio-ethanol production. The statement “biofuels production shall not create the problem of food competition” is generally defined as one of the criteria for sustainable biofuels [127-130]; this study, therefore, defines the resources potential for sustainable bio-ethanol production in Thailand as the feedstock surplus available after satisfying the demand for food and the other existing industries by considering both domestic and export demand. Even though assuming bio-ethanol as the last priority seems to be unfair, however, we suppose that policy makers should estimate the available resources by avoiding all probable consequential impacts to other current industries. The available feedstocks for biofuels production can be estimated from the following equation:

$$PQ_i = TQ_i - \sum_j CF_{i,j} \times D_Domestic_{i,j} - \sum_j CF_{i,j} \times D_Export_{i,j}$$

where PQ_i is the potential amount of feedstock i for biofuels production in a country (tons per year) and TQ_i is the total amount of feedstock i in a country (tons per year) for a period of time and $CF_{i,j}$ is the conversion factor to convert amount of feedstock i for producing product j and $D_Domestic_{i,j}$ is the total demand of product j for domestic consumption (tons per year) and $D_Export_{i,j}$ is the total demand of product j for export (tons per year). The parameters of land occupation and crops yield are included in the analysis to estimate TQ_i by $TQ_i = A_i \times Yield_i$. The term A_i is the plantation area of feedstock i in a country (square meter or rai per year), in case of first generation biofuels production and $Yield_i$ is the yield of feedstock i per unit of planted area (e.g. ton cassava per rai). Then, the Net feedstocks balance can be estimated by subtracting the projected feedstock requirements in the future from the estimated available feedstock resources. The conversion factors ($CF_{i,j}$)

for estimating the amounts of feedstock i required in order to produce ethanol and other products (products j) are summarized in **Table 3.7**.

Table 3.7 Conversion factors of various bio-ethanol feedstocks in Thailand

Feedstock (i)	Conversion factor ($CF_{i,j}$) of feedstock to produce bio-ethanol (litre ethanol/ton feedstock)		Conversion factor ($CF_{i,j}$) of feedstock to produce other products (kg feedstock/ kg product)	
	Baseline	Ranges	Product (j)	$CF_{i,j}$
Molasses (cane)	250 ^a	250 ^b -330 ^c	MSG	7 ^f
Sugarcane	70 ^a	70 - 80 ^d	Sugar	9.6 ^g
Cassava (fresh root)	180 ^a	167 ^e -180 ^b	Dried chips	2.1 ^g
			Pellets	2.1 ^g
			Flour/starch (dry)	4.2 ^g
			MSG	8.9 ^g
Cassava (dried chip)		333 ^e	Pellets	1 ^g

^a Committee on Energy, 2002 [131]; ^b TEI, 2007 [84]; Silalertruksa and Gheewala, 2009 [132];

^c Nguyen and Gheewala, 2008 [22]; ^d Macedo et al., 2008 [133]; ^e Nguyen et al., 2007 [19];

^f KAPI, 2007 [107]; ^g OAE, 2008 [99].

3.3.2 Shannon index

The diversity of supply can reveal the security of supply in terms that biofuels production will not rely on only one or two of supply sources and this is an important means to hedge against supply risks [134-136]. The study uses Shannon index as an indicator to measure diversity of feedstock supply for the future bio-ethanol production system in Thailand. Shannon index is a simple indicator often used for measuring the diversity of categorical data. It is not only used to compare diversity between habitat samples in ecology, but also to assess the diversity of fuels in energy security analysis [135-138]. In this study, Shannon index is applied to assess the long-term security of supply in terms of diversity of feedstock sources. A quantitative measure of either form of diversity i.e. variety and balance of supply sources can therefore serve as an indicator of security of supply. Stirling (1999) recommended three elements to be considered in measuring diversity i.e. variety (the number of categories), balance (the spread across categories) and disparity (the degree to which the categories are different from each other) [139]. However, no index including all the three elements exists given the difficulty to define disparity, therefore, today only the indices that measure the other two elements of diversity, formally called indices of 'dual concept' diversity, are developed [134]. The related equation to estimate the Shannon index is as follows:

$$I = -\sum_i (p_i \ln p_i)$$

where:

- I = the feedstocks supply security indicator;
- p_i = the share of feedstock resource i in the total biofuels supply system;
- i = the feedstock source index;

To apply the Shannon index to measure the security of feedstocks supply for bio-ethanol production, a key assumption is that only the diversity of feedstock sources is measured, the quality and values among those feedstocks will not be considered. This index increases with either the number of different supply sources or the balance among supply sources. Therefore, a higher value of Shannon index means that the assessed biofuel system will have more security of feedstock supply in terms of diversity of supply sources. However, the upper limit of the indicator depends on the number of feedstocks used in the system but it will generally not be higher than 2.

3.4 Phase IV: Employment impact analysis

This phase aims to assess employment and other socio-economic impacts of the biofuel production systems in Thailand compared to the petroleum fuel production systems. The key elements of socio-economic development are investigated including employment generation, economic effects on Gross Domestic Product (GDP) and trade balance. The functional unit used in the comparison is 1 TJ of biofuels/fuels. The scope of the assessment includes quantification of direct and indirect employment effects [140] of the existing biofuels in Thailand including bio-ethanol derived from cassava, molasses and sugarcane and biodiesel derived from oil palm. Direct employment is generated in cultivation and harvesting of feedstocks e.g. sugarcane, cassava and oil palm cultivation as well as in the biofuels processing industry. Indirect employment is generated in the industries that produce intermediate deliveries to the agriculture and biofuel processing sectors as shown in **Figure 3.5**. The study uses the “hybrid method”, a combination of the analytical approach (micro level) and Input-Output model (macro level), to investigate the employment effects of biofuels production in Thailand. The results are expected to describe the following questions i.e. (1) the number of persons would be engaged in biofuels production in Thailand; (2) the characteristics of employment; (3) the employment of biofuels production and its implications for social and socio-economic development in Thailand; and (4) the socio-economic effects of biofuels on the GDP and trade balance.

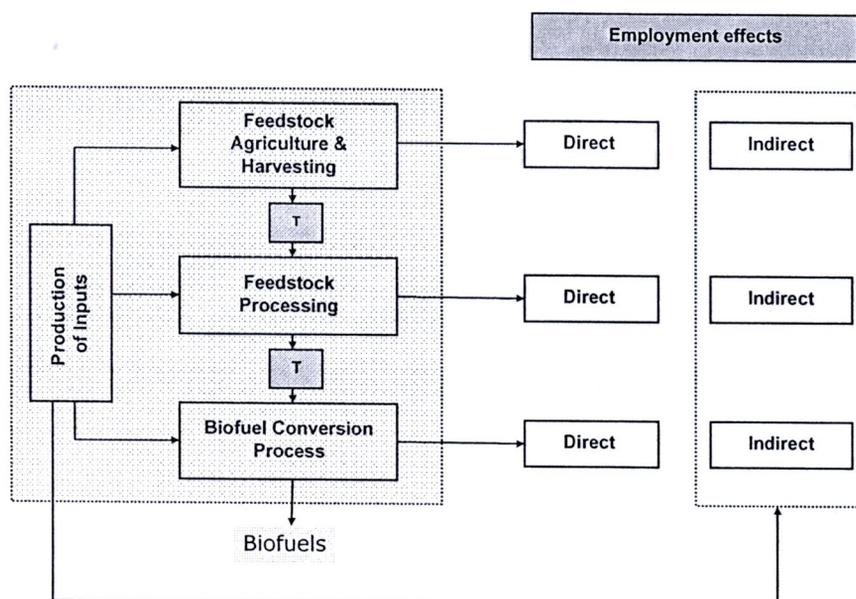


Figure 3.5 Scope of employment impacts analysis

3.4.1 Analysis of direct employment

This step estimates the effects on direct employments of feedstock cultivation and harvesting, feedstock processing and biofuels conversion using the production process analysis. For agriculture, the analysis of the expenditures for labours in cultivation and harvesting of cassava, sugarcane and molasses complemented with the annual wage data is used to determine the employment in feedstock cultivation and harvesting [141]. For the feedstock processing stage and biofuel conversion stage there are known number of producers and direct surveys and interviews have been performed to collect the actual number of employees in each factory. **Table 3.8** shows the assumptions for the crop productivity and biofuel conversion efficiency used in the study.

Table 3.8 Baseline crop productivity and conversion efficiency of Thai biofuel production

Feedstocks	Biofuels	Crop productivity (2005-2008)	Conversion efficiency (Litre biofuel/ton feedstock)
Sugar cane	Molasses ethanol	Average : 9.1 ton cane/rai Range : 7.4 – 10.9 ton cane/rai	<u>250</u> - 330
	Sugarcane ethanol		<u>70</u> – 80
Cassava	Cassava ethanol	Average : 3.4 ton roots/rai Range : 2.7 – 3.8 ton roots/rai	167 ^e – <u>180</u>
Oil palm	Palm oil biodiesel	Average : 2.6 ton FFB/rai Range : 2.5 – 2.8 ton FFB/rai	<u>158</u> - 182

3.4.1.1 Direct employment in agriculture

The direct employment in agriculture is calculated from the expenditures for goods and services during land preparation, feedstock plantation, treatment and harvesting and their share of labour costs. The potential number of direct employment in agriculture can be quantified by utilizing data on labour costs in feedstocks production divided by the average annual working-hours in agricultural sector in Thailand as following equation.

$$Employment_{agr} = \frac{PC_{feedstock} \times Labourshare}{AWG_{agr}}$$

where $Employment_{agr}$ is the agricultural employment in agriculture (person-year/rai); $PC_{feedstock}$ is the production costs of feedstock (THB/rai); $Labourshare$ is the share of labour cost in $PC_{feedstock}$ and AWG_{agr} is the average annual wage per employed person in agricultural sector of Thailand (THB/person-year). The production costs data of cassava, sugarcane and oil palm during from year 2005-2008 are collected from the Office of Agricultural Economics [142]; while, the wage data of agriculture in Thailand is referred from the National Statistical Office [143-145]. **Table 3.9** shows the estimated labour-force requirements for biofuel feedstocks cultivation and harvesting.

Table 3.9 The estimated direct employment coefficient of feedstocks production in Thailand

	Employment coefficients		
	(Person-yr/rai)	(Person-yr/ton)	(Person-yr/ML Biofuels)
Sugar cane	0.06 - 0.09	0.006 - 0.009	81 - 124
Cassava	0.03 - 0.05	0.008 - 0.013	34 - 52
Oil Palm	0.03 - 0.04	0.011 - 0.017	68 - 105

3.4.1.2 Direct employment in the processing sectors

The study determines the direct employment of feedstock processing and biofuel industries by collecting data about the number of employees and production capacities from 5 sugar mills, 5 dried-chip floors, 10 bio-ethanol plants and 4 palm biodiesel plants complemented with the secondary data of 17 palm oil mills [146]. The estimated employment generation coefficients for the relevant processing sectors in biofuel production systems in Thailand are shown in **Table 3.10**.

Table 3.10 Surveys of the employed persons in biofuels production chain

Stages	Units	Employment coefficients	
		Average	Range
Feedstock processing			
Sugar milling	Persons.year/1000 ton cane (TC)	0.36	0.29-0.47
Dried chips processing	Persons.year/Ton chips	0.01	
Palm oil milling	Persons.year/M.ton CPO	10.4	5.9-19
Biofuels conversion			
Cassava ethanol	Persons.year/ML	1.3	0.4-2.7
Molasses ethanol	Persons.year/ML	1.7	0.3-3.9
Sugarcane ethanol	Persons.year/ML	2.4	-
Palm oil biodiesel	Persons.year/ML	0.5	0.3-0.6

3.4.2 Analysis of indirect employment

To assess the indirect employment effects caused by biofuels production in Thailand, the study applies the most disaggregated format (180×180) of 2005 IO tables of Thailand in the analyses by aggregating it into a new format (50×50 major sectors) relevant to the biofuels production as listed in **Appendix C (Table C.1 – C.2)**. For Thailand, the IO tables are compiled and published by the National Economic and Social Development Board (NESDB) in four formats i.e. 16×16, 26×26, 58×58 and 180×180 sectors to show the inter-industrial linkages and are updated every five years [75, 147]. Every cell of transaction value in this newly grouped IO tables is at purchasers' prices wherein the trade margin (wholesale plus retailed), transportation cost and import are included. To quantify the net employment (direct plus indirect employment) of biofuels, the following steps of data preparation have been done.

3.4.2.1 Determining the Leontief inverse matrix

First of all, the study uses the new aggregated 2005 IO tables (50×50 sectors) to calculate the input coefficient matrix (A) and the inverse matrix $(I - A)^{-1}$ as shown in Appendix C (Table C.3). This is to see how many production values of each sector are directly and indirectly necessary (including imports) to produce products worth 1 Million THB.

3.4.2.2 Determining the direct employment vector

Secondly, the direct employment coefficients i.e. the direct labour requirement per unit of output in each sector are identified to indicate the number of persons employed per

unit of output. In this study, the direct employment coefficient is denoted by $l_1, l_2, l_3, \dots, l_n$ and can be determined as:

$$l_i = \frac{L_i}{X_i} \quad (i = 1, 2, 3, \dots, n)$$

where l_i is the direct employment coefficient of sector (i); L_i is the total employment of the sector (i); and X_i is the gross output of the sector (i). These estimated direct labour coefficients will be used to constitute the “direct employment vector”, $L = (l_1, l_2, l_3, \dots, l_n)$ [148]. The number of employed persons (age over 15 years) in each economic sector (L_i) are compiled from the Labour force survey (LFS) in year 2005 [149] and the Industrial Census year 2007 [150] of the National Statistical Office (NSO). The total output of each economic sector (X_i) is referred from the 2005 IO tables. Then, the unit of direct employment coefficient (l_i) would be the number of employment (persons-year) according to a demand of 1 Million THB in that economic sector as shown in **Table 3.11**.

3.4.2.3 Determining the total employment coefficients

Thirdly, the total direct and indirect employment generated per unit of final demand in a given sector is calculated by multiplying the inverse matrix $(I - A)^{-1}$ with the direct employment vector (L). The sum each row shows the total employment generated (E_j) by 1 million THB increase in the final demand of sector (j). From this, indirect employment coefficients can also be determined by subtracting the direct employment coefficient from the total employment coefficient of each sector. Thus, the quantity of employment both direct and indirect for a demand of 1 Million THB can be estimated as shown in **Appendix C** (Table C.4). In addition, the employment multiplier (e_j) can be derived as the ratio of total employment generated to the direct employment requirement per unit of output in the given sector. Hence, the employment multiplier can be given by, $e_j = \frac{E_j}{l_j}$ ($j = 1, 2, 3, \dots, n$).

3.4.2.4 Quantifying the employment impacts of biofuels production

To quantify the employment impacts caused by biofuel production, the final demand vectors (F) of molasses ethanol, cassava ethanol, sugarcane ethanol and palm biodiesel are determined by breaking down their production costs into the cost items; thereafter, each cost item is assigned to one of the sectors defined for the former IO tables.

The breakdown of biofuel production costs in Thailand are obtained from previous studies on life cycle costing of biofuels in Thailand [61, 151-152] and the relevant economic sectors for each cost items are summarized in **Table 3.11**.

Table 3.11 The breakdown of biofuels production costs in Thailand

	Inputs to biofuels production in Thailand (THB/L biofuel)			Related sectors in IO tables
	Cassava ethanol	Molasses ethanol	Palm biodiesel	
Feedstock cost				
Cassava (fresh roots)	10.53			002
Molasses Sugarcane		14.00		016 003
FFB			22.34	004
Feedstock processing cost				
Dried chips	0.44			015
CPO			2.21	017
Labour cost (ethanol)	0.59	1.18		019
Labour cost (biodiesel)			0.51	027
Energy	2.38	1.60	0.82	039
Water	0.06	0.06	0.05	041
Wastewater treatment	0.58	0.77	0.10	048
Chemicals	1.54	0.30	0.93	024
Methanol			3.95	019
Maintenance	0.35	0.30	0.02	050
Depreciation	1.22	1.15	0.65	034
Admin & Selling	0.50	0.59	0.25	050
Miscellaneous e.g. insurance, interest	0.12	0.18	0.38	047
Total	18.32	20.13	32.20	

