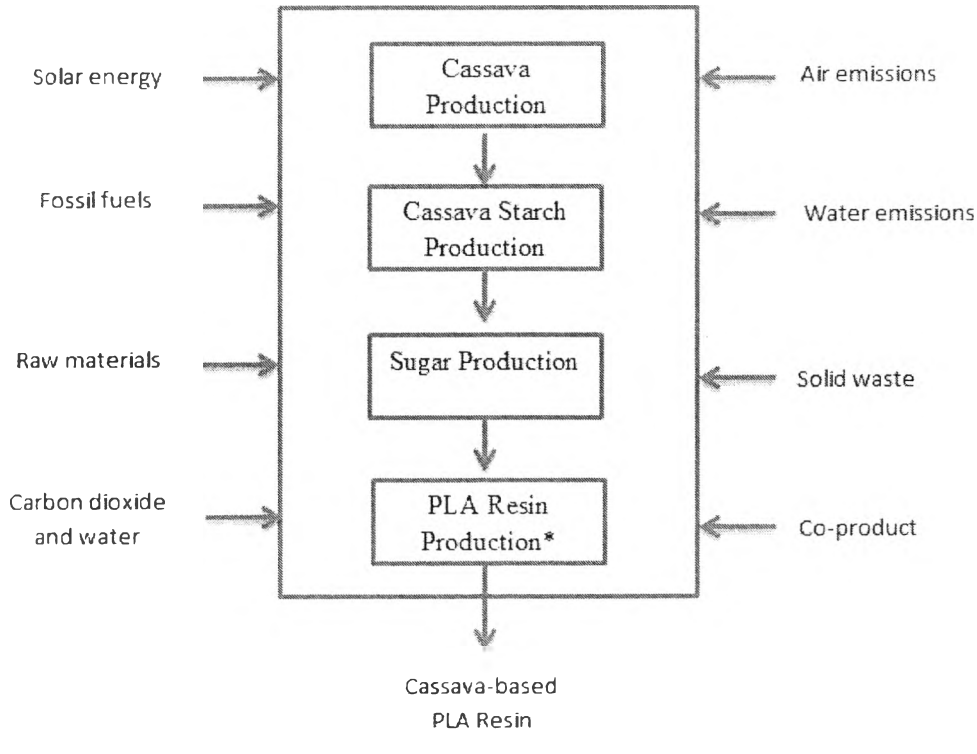
CHAPTER IV
RESULTS AND DISCUSSION

4.1 Life Cycle Inventory

4.1.1 PLA Resin Production

As PLA resin was produced in Thailand by PURAC so the production of PLA resin based on PURAC (Thailand) is used as a base model for this study with a modification that cassava is to be used instead of sugar. The system boundary for LCI of the PLA resin production is shown in Figure 4.1. After cassava production (cultivation, harvesting and transportation), cassava is converted to starch before convert to sugar and entering the resin production stage. The final product which is resin is called "Cassava-based PLA Resin".



** Including: Lactic Acid and Lactide Production*

Figure 4.1 The production of PLA resin in Thailand.

4.1.1.1 Cassava Production

In cassava production consists of four major steps:

1) Land preparation before planting by soil tillage to eliminate the weed and create the trench for cultivation.

2) Preparation of breeding and cultivation, cassava strains were selected and were chopped to appropriate size for cultivation. Then place them in the trench.

3) The maintenance: Consists of important events such as eliminate the weeds by tillage and use chemicals. Including put the fertilizer. Farmers tend to use both manure and chemical fertilizers

4) Harvesting can be done by using machine harvesting or workers.

The cassava production can be expressed as follows.

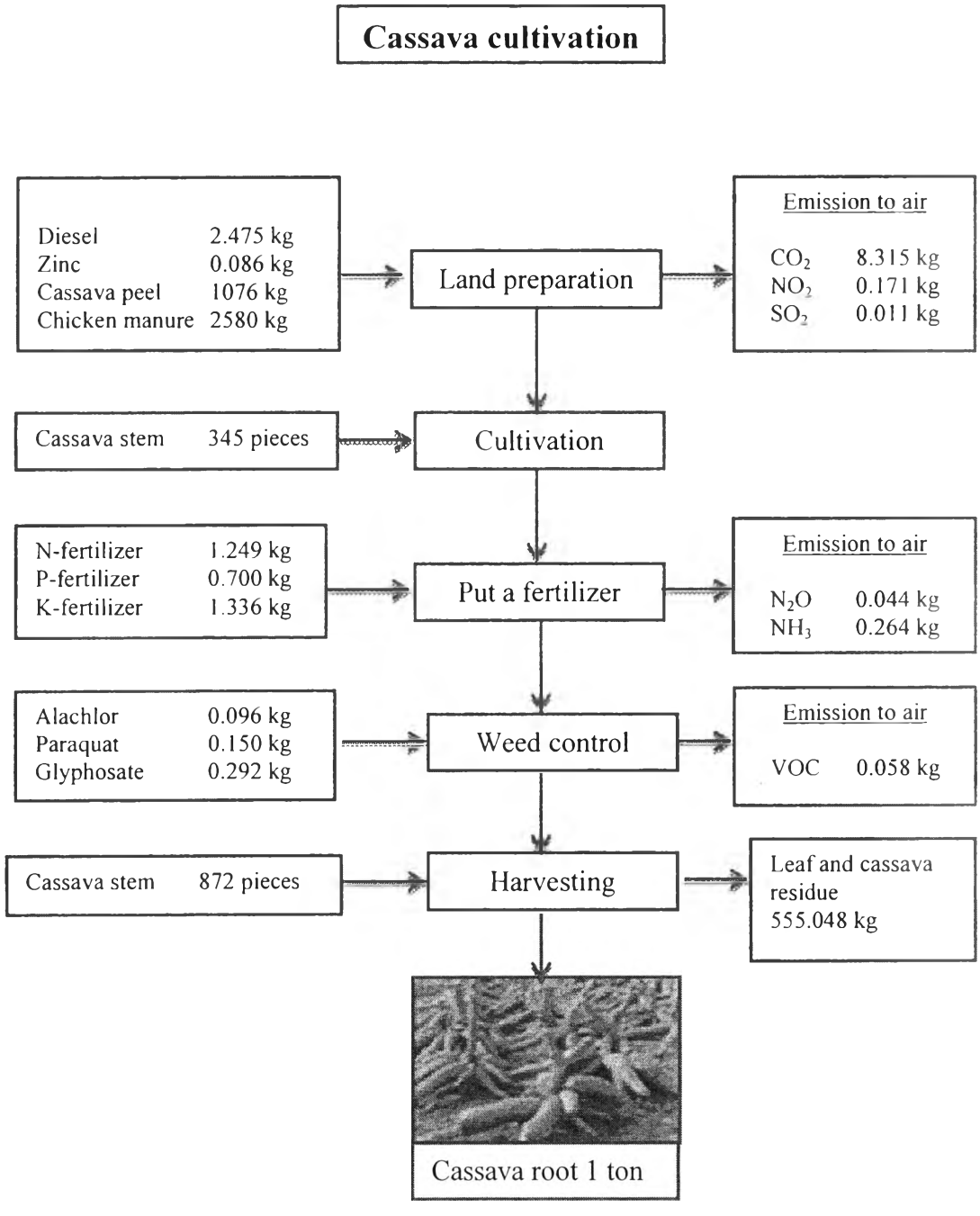


Figure 4.2 The process procedure of cassava cultivation in rainy season with water (Khongsiri, 2009).

The Data for CO_2 uptake during cassava plantation (-188,614 g CO_2 /ton chip) were extracted from Leng *et al.* (2008) and used in the cassava production stage. The inventory average of cassava production is shown in Table 4.1.

Table 4.1 Results of the inventory analysis of one ton of cassava root (Khongsiri, 2009)

Input			Output		
Type	**Quantity**	**Unit**	**Type**	**Quantity**	**Unit**
Raw material			**Products**		
Cassava stems	345	pieces	cassava root	1000	kg
cassava peel	1076	kg	cassava residue	555.04	kg
chicken manure	2580	kg	Cassava stems	872	piece
N-fertilizer	1.24	kg	**Air emissions**		
P-fertilizer	0.70	kg	carbondioxide	8.32	kg
K-fertilizer	1.34	kg	nitrogenoxide	0.17	kg
Alachlor	0.09	kg	sulfurdioxide	0.01	kg
Paraquat	0.15	kg	nitrousoxide	0.04	kg
Glyphosate	0.29	kg	ammonia	0.26	kg
Zinc	0.09	kg	volatile organic compound	0.06	kg
Fuel					
Diesel	2.48	kg			

4.1.1.2 Cassava Starch Production

At plant, cassava production process mainly use dewatering centrifugal method which consist of main step as follows

Cassava roots are firstly delivered to a sand removal drum and then to a rinsing gutter for cleansing and peel separation. After washing, the clean cassava roots are sent to a chopper to chop into small pieces (approximately 20–25 mm) and then taken to a rasper. During rasping, water is added to facilitate the process. The resulting slurry, consisting of starch, water, fiber, and impurities, is then pumped into the centrifuges for extraction of the starch from the fibrous residue (cellulose). The extraction system consists of three or four centrifuges in series. There are two types of extractors: a coarse extractor with a perforated basket and a fine extractor with a filter cloth. Suitable amount of water and sulfur-containing water are constantly applied to the centrifuges for dilution and bleaching of the starch. The starch slurry is then separated into starch milk and fibrous residue. The

coarse and fine pulp is passed to a pulp extractor to recover the remaining starch and the extracted pulp is then delivered to a screw press for dewatering. The dewatered fibrous residue is sold to a feedstock mill. The starch milk from the fine extractor is pumped into a two-stage separator for impurity removal from the protein. After passing to a second dewatering machine, the starch milk has the starch content up to 18–20 Baume´ (Orathai and Maneerat, 2008). Then, the concentrated starch milk is pumped into dehydration horizontal centrifuges (DHC) to remove water before drying. The DHC consists of filter cloth placed inside, rotating at about 1000 rpm to remove water from the starch milk. The resulting starch cake has a moisture content of 35–40%. The starch cake is taken to a drying oven consisting of a firing tunnel and drier stack. Drying is effected by hot air produced by oil burners. During the drying process, the starch is blown from the bottom to the top of the drier stack and then fallen into a series of two cyclones in order to cool down the starch. The dried starch with a moisture content of less than 12% is conveyed through a sifter for size separation and finally packaging. Shown in Fig. 4.3 is the production process of cassava starch to which no biogas production lines are applied.

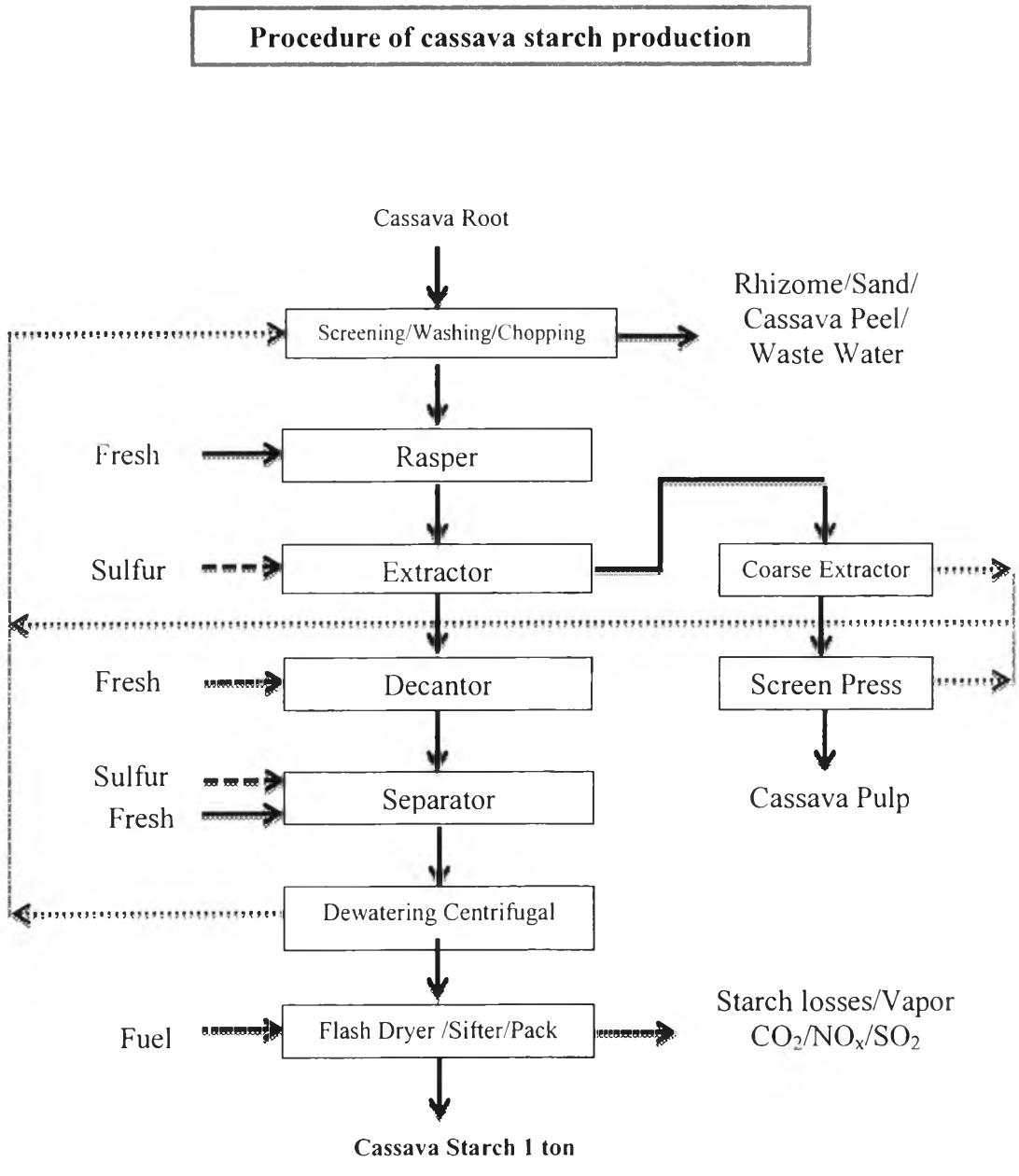


Figure 4.3 The process procedure of cassava starch production (Khongsiri, 2009).

The inventory analysis of cassava starch production is shown in Table 4.2.

Table 4.2 Results of the inventory analysis of one ton of cassava starch (Khongsiri, 2009)

Input			Output		
Type	**Quantity**	**Unit**	**Type**	**Quantity**	**Unit**
Raw material			**Product**		
cassava root	4,803.10	kg	cassava starch	1000	kg
sulfur	0.95	kg	**By products**		
water	12,435.76	kg	cassava peel	135.99	kg
Fuel/Electricity			Rhizome	68.22	kg
Fuel oil	34.50	L	cassava residue	1457.28	kg
Electricity	176.77	Kwh	sand	20.00	kg
			Waste		
			starch losses	121.58	kg
			Air emissions		
			carbondioxide	61.53	kg
			nitrogenoxide	252.27	g
			sulfurdioxide	330.96	g
			vapor	212.63	kg
			Water emissions		
			Waste water	13664.65	kg
			BOD	127.57	kg
			COD	265.13	kg
			total nitrogen	6.50	kg
			total phosphorus	0.40	kg
			Suspended solids	90.05	kg

The inventory data for cassava starch production which include biogas system and using biogas in production line were received from company. Shown in Fig. 4.4 is the production process of cassava starch with biogas production lines are applied. And the inventory analysis of cassava starch production with biogas system is shown in Table 4.3.

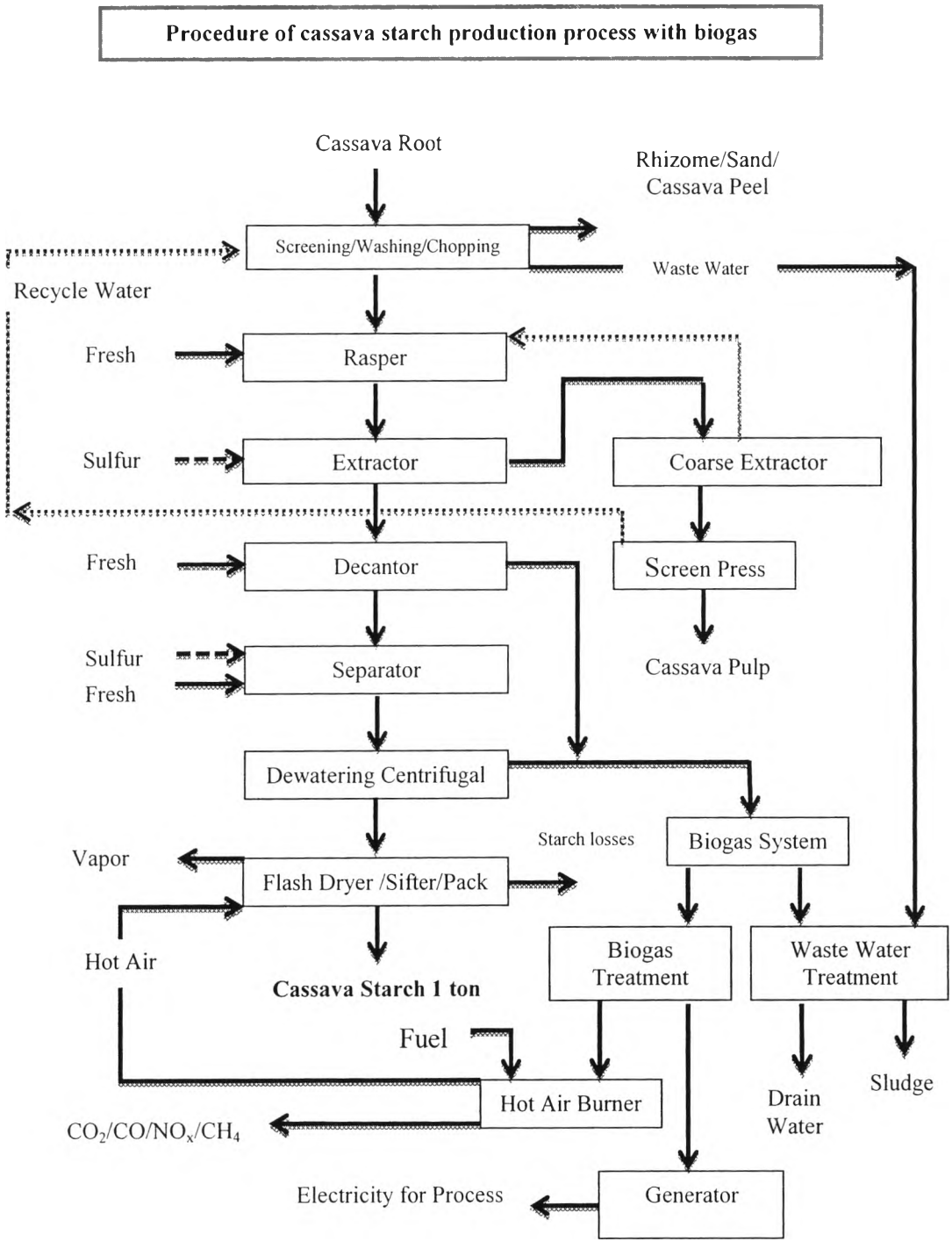


Figure 4.4 The process procedure of cassava starch production with biogas production line (Khongsiri, 2009).

Table 4.3 Results of the inventory analysis of one ton of cassava starch with biogas production line

Input			Output		
Item	**Quantity**	**Unit**	**Item**	**Quantity**	**Unit**
Raw material			**Product**		
cassava root	4,500	kg	cassava starch	1000	kg
sulfur	0.55	kg	**By products**		
water	12.67	m^3	cassava peel	248.60	kg
Fuel/Electricity			Rhizome	24.84	kg
Electricity	121.06	Kwh	cassava residue	460.47	kg
Fuel oil	1.19	kg	sand	17.71	kg
			Air emissions		
			carbondioxide	4.13	kg
			nitrogenoxide	0.04	kg
			carbonmonoxide	4.40E-03	kg
			sulfur oxide	7.30E-03	kg
			Water emissions		
			Waste water	19.63	m^3
			BOD	0.93	kg
			COD	4.17	kg
			suspended solids	3.33	kg
			TDS	65.66	kg
			Oil & grease	0.22	kg

4.1.1.3 Sugar Production

Glucose syrup production from cassava can be subdivided into the following process areas of liquefaction, saccharification, and purification.

Native starch consists of microscopic granules having a complex internal structure. At room temperature, these granules are insoluble in water. However, if starch slurry is heated above 60 $^{\circ}$C, the granules will swell and eventually rupture. This results in a dramatic increase in viscosity. At this point, the starch has been "gelatinized". The gelatinized starch is now susceptible to attack by amylase enzymes. In practice, cassava starch in gelatinized and partially hydrolyzed very rapidly in one step (see flow chart) by heat-stable amylase. This step is called

liquefaction. The partially degraded starch chains called dextrins are suitable starting materials for the later steps in syrup production.

- **Liquefaction**

Starch slurry is made with 30-35% dry solids and its pH is adjusted to 6.0-6.4. Calcium is added using calcium hydroxide or calcium chloride. Calcium ions stabilize the enzyme. A heat-stable a-amylase (Novo's Termamyl 120 L) is mixed into the slurry, and then the slurry is instantaneously heated to 100 ^{o}C and held at this temperature for 10 min before it is cooled to 90 ^{o}C. This temperature is maintained for 1-3 h to further hydrolyze the starch. At the end of this step, the starch has been converted to dextrins with a dextrose equivalent (DE) between 8 and 15. (The physical properties of the syrup vary with the DE and the method of manufacture.) DE is the total reducing sugar in the syrup expressed as dextrose on a dry weight basis.

- **Saccharification**

After liquefaction, the pH is reduced to between 4.2 and 4.5 and the solution is cooled to 60 ^{o}C. A glucomylase (Novo's AMG 300L) is added immediately. The reaction time for saccharification is usually between 24-48 h depending on enzyme dose. Glucoamylase releases single glucose units from the ends of dextrin molecule. Syrups of 95% glucose or higher are manufactured, e.g., a typical 98 DE syrup could have the sugar profile as shown in the flow chart.

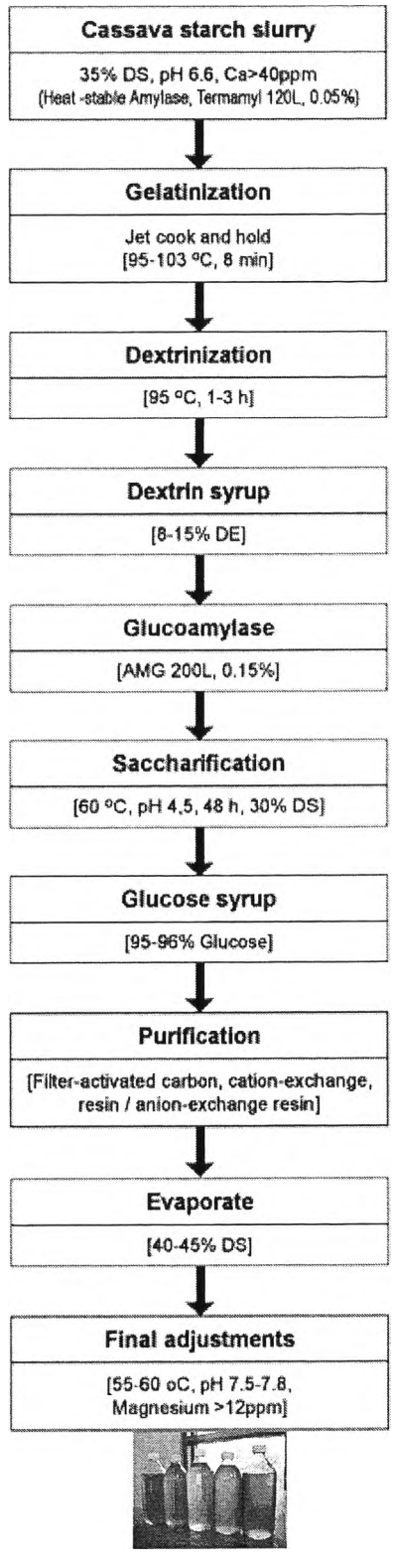


Figure 4.5 Flow chart for glucose syrup production from cassava (Source: http://www.cassavabiz.org/postharvest/gsyrup01.htm).

The inventory analysis of sugar production is shown in Table 4.4.

Table 4.4 Results of the inventory analysis of one ton of sugar

Input			Output		
Item	**Quantity**	**Unit**	**Item**	**Quantity**	**Unit**
Raw material			**Product**		
cassava starch	1.05	ton	Sugar(D-glucose)	1.00	ton
Sulfuric acid (100%)	1.21	kg	**Water emissions**		
Sodium hydroxide (50%)	0.76	kg	waste water	6.89	m^3
water	27	m^3			
Fuel/Electricity					
Fuel oil	6.67	L			
Electricity	144	kWh			

4.1.1.4 PLA Resin Production

In this part, the inventory data from Wim J. Groot & Tobias Borén (2010) were used as the secondary data for the production of PLA resin of PURAC (Thailand). Based on PURAC's inventory data, the inventory data for Cassava-based PLA resin were constructed step-by-step in this study. First, the sugarcane production data were carefully taken out from Purac's inventory data based on data from Nguyen (2007) and then replaced by the secondary data (Khongsiri, 2009), for cassava starch without biogas using secondary data (Khongsiri, 2009) and for cassava starch with biogas using data from company. The inventory data for sugar production were extracted from literatures (Chiarakorn *et al.*, 2011) and (Renouf *et al.*, 2008). Table 4.5 shows the inventory analysis of the production of Cassava-based PLA resin.

Table 4.5 Results of the inventory analysis of one kilogram Cassava-based PLA resin

Input			Output		
Type	**Quantity**	**Unit**	**Type**	**Quantity**	**Unit**
Raw material			**Product**		
Sugar	1.35	kg	PLLA resin	1	kg
Lime	0.51	kg	**Water emissions**		
Sulfuric acid	0.64	kg	waste water	8.00E-05	kg
(NH4)2SO4	0.03	kg			
ammonia	0.01	kg			
phosphoric acid	0.02	kg			
Fuel/Electricity					
Diesel for inbound transportation	0.02	L			
Electricity	1.09	kWh			
Steam	0.65	kg			

4.1.2 PBS Resin Production

In this part, the secondary data from the key player were used for the inventory data of the production of PBS resin. A simple process diagram of PBS resin production is shown in Figure 4.6. The primary data for sugar production from sugarcane were retrieved from MTEC. Data for CO_2 uptake during sugarcane plantation (-0.189 kg CO_2/kg sugarcane) were extracted from Nguyen and Gheewala (2008). Due to the secrecy agreement, the inventory data of PBS resin production were not included in this report. Tables 4.6 and 4.7 show the inventory data of the sugarcane plantation and sugarcane milling in Thailand respectively.

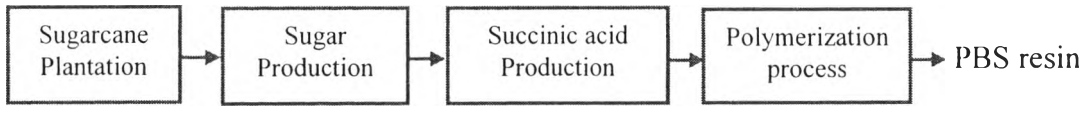


Figure 4.6 A simple process diagram of PBS resin production.

Table 4.6 Results of the inventory analysis of sugarcane plantation in Thailand

Input			Output		
Type	**Unit**	**Amount**	**Type**	**Unit**	**Amount**
Fuel			***Product***		
Diesel	liter	1.42E-03	Sugarcane	kg	1
Chemical:			***Co-product***		
Fertilizer (N)	kg	1.78E-03	Cane trash - 0% burning	kg	0.20
Fertilizer (P)	kg	8.29E-04			
Fertilizer (K)	kg	7.39E-04			
Paraquat	kg	1.28E-05			
Atrazine	kg	4.49E-05			
Ametryne	kg	3.21E-05			
2,4-D	kg	1.29E-05			

Table 4.7 Results of the inventory analysis of sugarcane milling in Thailand

Input Inventory		
Type	**Unit**	**Amount**
Raw material		
Sugarcane plant	kg	128.36
Energy		
Production of Electricity	kg	35.73
& Steam Bagasse mainly & other		
-Electricity from bagasse	kWh	2.23
-Steam from bagasse	kg	57.72
Chemical		
Lime	kg	0.27
Sodium chloride	kg	0.10
Hydrochloric acid	kg	5.78E-05
SiO_2	kg	2.97E-04
Biocide	kg	4.70E-04
Aluminium sulfate	kg	4.79E-04
Caustic soda flake	kg	1.49E-04

Flocculants	kg	4.95E-03
Miscellaneous	kg	7.34E-04
Output Inventory		
Type	**Unit**	**Amount**
Product		
Raw sugar	kg	10.18
White sugar	kg	1.00
Pure white sugar	kg	2.89
Co-product		
Molasses	kg	4.66
Surplus bagasse and others	kg	11.80
Electricity for sale	kWh	0.58

4.1.3 Production of Plastic Product

In this study, garbage bag was selected as model product for PLA and PBS products. During the collection of data and interview with the manufacturers, we have found that bioplastic resins are not easy to process and the manufacturers also are not familiar with processing bioplastic, resulting in low productivity of processing bioplastic resin into products when compared to conventional plastics. The transportations of PLA resin and PLA product were also included in this part as described in the methodology chapter.

4.1.3.1 Garbage Bag

Garbage bag is a bag that use for collecting waste and is produced by using blown film extrusion process. Table 4.8 indicates specifications of garbage bag.

Table 4.8 Specifications of garbage bag

Bioplastic Product	Size	Weight (per piece)
Garbage bag	20"×25"	0.025 kg

Garbage bag data were collected from the company according to the process shown in Figure 4.7 and 4.8. Their processes are slightly

different but the main process is similarity. The process consists of four main steps: blowing, printing, cutting and recycling. In the recycling part, information was given by the manufacturers that scraps from bioplastic processing can be recycled up to only 5 % of the virgin resin fed to the process. Results of the inventory analysis of garbage bag production from company based on one kg of bioplastic product are shown in Table 4.9.

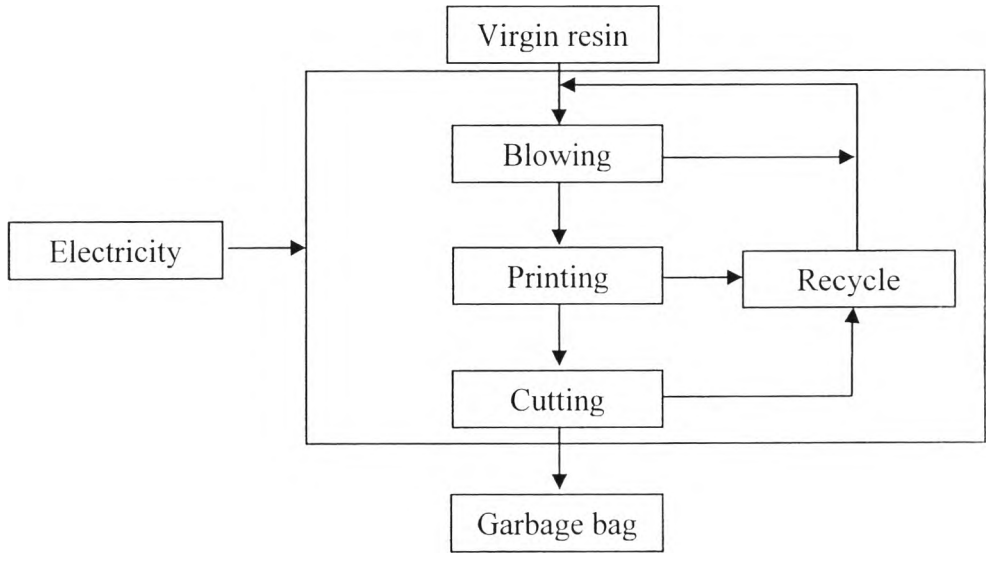


Figure 4.7 Garbage bag production process from bioplastic.

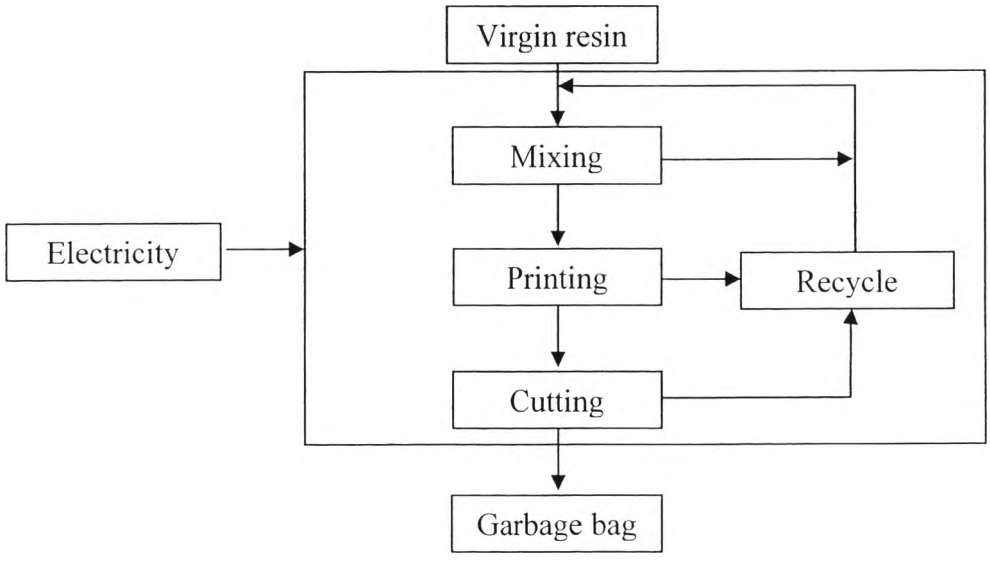


Figure 4.8 Garbage bag production process from conventional plastic.

Table 4.9 Results of the inventory analysis of PLA garbage bag production from company based on one kg of bioplastic product

Transportation of PLA resin					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Product***		
Diesel	kg	3.11E-03	Cassava-based PLA resin	kg	1.10
			Emissions to air		
			Carbon dioxide (CO_2)	g	9.77
			Carbon monoxide (CO)	g	0.03
			Nitrogen oxides (NO_x)	g	0.10
			Particulate matter (PM)	g	7.55E-03
			Hydrocarbons (HC)	g	8.74E-03
			Methane (CH_4)	g	2.18E-04
			Benzene (C_2H_6)	g	1.66E-04
			Toluene (C_7H_8)	g	6.99E-05
			Xylene (C_8H_{10})	g	6.99E-05
			Non – methane volatile organic compounds (NMVOCs)	g	1.67E-02
			Sulfur oxides (SO_x)	g	2.11E-03
			Nitrous Oxide (N_2O)	g	3.87E-03
			Cadmium	g	3.00E-08
			Copper	g	5.11E-06
			Chromium	g	1.50E-07
			Nickel	g	2.10E-07
			Selenium	g	3.00E-08
			Zinc	g	3.00E-06
			Lead	g	3.32E-10
			Mercury	g	6.00E-11

Drying					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Product***		
PLA resin	kg	1.10	Dried PLA resin	kg	1.10
Utilities					
Electricity	kWh	3.65E-02			

Blowing & Printing					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			***Product***		
Virgin PLA resin	kg	1.10	Uncut bag	kg	1.08
Recycle PLA resin	kg	5.38E-02	***Solid Waste***		
Printing color A	kg	6.15E-02	Scrap	kg	7.69E-02
Utilities					
Electricity for blowing	kWh	0.28			
Electricity for printing	kWh	0.08			

Cutting					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Product***		
Printed bag	kg	1.08	Garbage bag	kg	1.00
Utility			***Solid Waste***		
Electricity	kWh	0.12	Scrap	kg	7.69E-02

Recycling					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Product***		
Scrap	kg	5.38E-02	Recycle PLA resin	kg	5.38E-02
Utility					
Electricity	kWh	1.26E-02			

Transportation of PLA product					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			***Product***		
Diesel	kg	3.08E-03	PLA Garbage bag	kg	1.00
Barge	kgkm	6.50	***Emissions to air***		
			Carbon dioxide (CO_2)	g	9.69
			Carbon monoxide (CO)	g	3.31E-02
			Nitrogen oxides (NO_x)	g	9.98E-02
			Particulate matter (PM)	g	7.49E-03
			Hydrocarbons (HC)	g	8.66E-03
			Methane (CH_4)	g	2.16E-04
			Benzene (C_2H_6)	g	1.65E-04
			Toluene (C_7H_8)	g	6.94E-05
			Xylene (C_8H_{10})	g	6.94E-05
			Non – methane volatile organic compounds (NMVOCs)	g	1.65E-02
			Sulfur oxides (SO_x)	g	2.09E-03
			Nitrous Oxide (N_2O)	g	3.84E-04
			Cadmium	g	2.98E-08
			Copper	g	5.06E-06
			Chromium	g	1.49E-07
			Nickel	g	2.09E-07
			Selenium	g	2.98E-08
			Zinc	g	2.98E-06
			Lead	g	3.29E-10
			Mercury	g	5.95E-11

At present, the garbage bag that produced from PBS has not been produced in Thailand so the product and the process are assumed to be the same as PLA garbage bag. Variables and the inventory data such as electricity, plastic resin input, plastic product, and scraps were assumed to be the same as PLA bag production. Table 4.10 shows the inventory data of PBS garbage bag.

Table 4.10 Results of the inventory analysis of PBS garbage bag production based on one kg of bioplastic product

Transportation of PBS resin					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Product***		
Diesel	kg	3.11E-03	PBS resin	kg	1.10
			Emissions to air		
			Carbon dioxide (CO_2)	9.77	9.77
			Carbon monoxide (CO)	0.03	3.34E-02
			Nitrogen oxides (NO_x)	0.10	0.10
			Particulate matter (PM)	7.55E-03	7.55E-03
			Hydrocarbons (HC)	8.74E-03	8.74E-03
			Methane (CH_4)	2.18E-04	2.18E-04
			Benzene (C_2H_6)	1.66E-04	1.66E-04
			Toluene (C_7H_8)	6.99E-05	6.99E-05
			Xylene (C_8H_{10})	6.99E-05	6.99E-05
			Non – methane volatile organic compounds (NMVOCs)	1.67E-02	1.67E-02
			Sulfur oxides (SO_x)	2.11E-03	2.11E-03
			Nitrous Oxide (N_2O)	3.87E-03	3.87E-04
			Cadmium	3.00E-08	3.00E-08
			Copper	5.11E-06	5.11E-06
			Chromium	1.50E-07	1.50E-07
			Nickel	2.10E-07	2.10E-07
			Selenium	3.00E-08	3.00E-08
			Zinc	3.00E-06	3.00E-06
			Lead	3.32E-10	3.32E-10
			Mercury	6.00E-11	6.00E-11

Drying					
Input Inventory			Output Inventory		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Product***		
PBS resin	kg	1.10	Dried PBS resin	kg	1.10
Utility					
Electricity	kWh	3.65E-02			

Blowing & Printing					
Input Inventory			Output Inventory		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			***Producs***		
Virgin PBS resin	kg	1.10	Uncut bag	kg	1.08
Recycle PBS resin	kg	5.38E-02	***Solid Waste***		
Printing color A	kg	6.15E-02	Scrap	kg	7.69E-02
Utilities					
Electricity for blowing	kWh	0.28			
Electricity for printing	kWh	0.08			

Cutting					
Input Inventory			Output Inventory		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Product***		
Printed bag	kg	1.08	Garbage bag	kg	1.00
Utility			***Solid Waste***		
Electricity	kWh	0.12	Scrap	kg	7.69E-02

Recycling					
Input Inventory			Output Inventory		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Product***		
Scrap	kg	5.38E-02	Recycle PBS resin	kg	5.38E-02
Utility					
Electricity	kWh	1.26E-02			

Transportation of PBS product					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			***Product***		
Diesel	kg	3.08E-03	PBS Garbage bag	kg	1.00
Barge	kgkm	6.50	***Emissions to air***		
			Carbon dioxide (CO_2)	g	9.69
			Carbon monoxide (CO)	g	3.31E-02
			Nitrogen oxides (NO_x)	g	09.98E-02
			Particulate matter (PM)	g	7.49E-03
			Hydrocarbons (HC)	g	8.66E-03
			Methane (CH_4)	g	2.16E-04
			Benzene (C_2H_6)	g	1.65E-04
			Toluene (C_7H_8)	g	6.94E-05
			Xylene (C_8H_{10})	g	6.94E-05
			Non – methane volatile organic compounds (NMVOCs)	g	1.65E-02
			Sulfur oxides (SO_x)	g	2.09E-03
			Nitrous Oxide (N_2O)	g	3.84E-04
			Cadmium	g	2.98E-08
			Copper	g	5.06E-06
			Chromium	g	1.49E-07
			Nickel	g	2.09E-07
			Selenium	g	2.98E-08
			Zinc	g	2.98E-06
			Lead	g	3.29E-10
			Mercury	g	5.95E-11

The inventory data for garbage bag production that produced from conventional plastics are shown in Table 4.11.

Table 4.11 Results of the inventory analysis of garbage bag production from polyethylene based on one kg of garbage bag

Transportation of HDPE,LDPE and LLDPE resin					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Products***		
Diesel	kg	2.78E-03	HDPE & LDPE and LLDPE resin	kg	0.98
			Emissions to air		
			Carbon dioxide (CO_2)	g	8.74
			Carbon monoxide (CO)	g	2.99E-02
			Nitrogen oxides (NO_x)	g	8.99E-02
			Particulate matter (PM)	g	6.75E-03
			Hydrocarbons (HC)	g	7.81E-03
			Methane (CH_4)	g	1.95E-04
			Benzene (C_2H_6)	g	1.48E-04
			Toluene (C_7H_8)	g	6.25E-05
			Xylene (C_8H_{10})	g	6.25E-05
			Non – methane volatile organic compounds (NMVOCs)	g	1.49E-02
			Sulfur oxides (SO_x)	g	1.88E-03
			Nitrous Oxide (N_2O)	g	3.46E-04
			Cadmium	g	2.68E-08
			Copper	g	4.57E-06
			Chromium	g	1.34E-07
			Nickel	g	1.88E-07
			Selenium	g	2.68E-08
			Zinc	g	2.68E-06
			Lead	g	2.96E-10
			Mercury	g	5.37E-11

Mixing					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			***Product***		
HDPE	kg	0.68	Mixed resin	kg	1.07
LDPE	kg	0.21			
LLDPE	kg	0.09			
Recycle resin	kg	5.36E-02			
Master batch	kg	3.43E-02			
Utilities					
Electricity	kWh	1.79E-03			

Blowing & Printing					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			***Product***		
Mixed resin	kg	1.07	Uncut bag	kg	1.02
Printing color A	kg	1.37E-03	***Solid Waste***		
Toluene	kg	4.20E-02	Scrap	kg	0.05
Isopropanol	kg	2.10E-02			
Ethanol 99.7 %	kg	6.98E-03			
Utilities					
Electricity for blowing	kWh	0.36			
Electricity for printing	kWh	7.50E-02			

Cutting					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Product***		
Printed bag	kg	1.02	Garbage bag	kg	1.00
Utility			***Solid Waste***		
Electricity	kWh	0.12	Scrap	kg	0.02

Recycling					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Product***		
Scrap	kg	5.36E-02	Recycle resin	kg	5.36E-02
Utility					
Electricity	kWh	2.50E-02			

Transportation of conventional garbage bag					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Product***		
Diesel	kg	3.01E-03	Garbage bag	kg	1.00
Barge	kgkm	6.50	***Emissions to air***		
			Carbon dioxide (CO_2)	g	9.69
			Carbon monoxide (CO)	g	0.03
			Nitrogen oxides (NO_x)	g	9.98E-02
			Particulate matter (PM)	g	7.49E-03
			Hydrocarbons (HC)	g	8.66E-03
			Methane (CH_4)	g	2.16E-04
			Benzene (C_2H_6)	g	1.65E-04
			Toluene (C_7H_8)	g	6.94E-05
			Xylene (C_8H_{10})	g	6.94E-05
			Non – methane volatile organic compounds (NMVOCs)	g	1.65E-02
			Sulfur oxides (SO_x)	g	2.09E-03
			Nitrous Oxide (N_2O)	g	3.84E-04
			Cadmium	g	2.98E-08
			Copper	g	5.06E-06
			Chromium	g	1.49E-07
			Nickel	g	2.09E-07
			Selenium	g	2.98E-08
			Zinc	g	2.98E-06
			Lead	g	3.29E-10
			Mercury	g	5.95E-11

4.1.4 Disposal Phase

The past waste management of Sa-med island has three different waste treatment scenarios: landfill without energy recovery, incineration without energy recovery and recycle. After composting plant was built for NIA project, the waste management was change to new different waste treatment scenarios: composting, incineration without energy recovery and recycle. In this research, the inventory analysis of end of life phase involves the collection and computation of data to quantify relevant inputs and outputs of the system, including utilities, the use of energy, and emissions to air. The inventory data were further analyzed for relevant environmental impacts as greenhouse gases emissions (GHG) by SimaPro 7.1 with CML2000 baseline methodology.

Table 4.12 Scenarios for waste management

Waste management scenario	% Landfill without energy recovery	% Composting	% Incineration	% Recycle
Current scenario	40	40	-	20
Scenario with bioplastic	-	40	40	20

4.1.4.1 Transportation for Waste Collection

The transportation bio-plastic waste from household to disposal site (composting plant at Sa-med) is approximately 10 km by using 6-wheel truck at full load 8.5 tons and go through all kind of hardships and difficulties condition.

Table 4.13 Emissions from transportation for waste collection

Transportation of PLA resin					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			***Product***		
Diesel	kg	2.12E-04	Plastic waste	kg	1.00
			Emissions to air		
			Carbon dioxide (CO_2)	g	0.67
			Carbon monoxide (CO)	g	1.40E-03
			Nitrogen oxides (NO_x)	g	2.69E-03
			Particulate matter (PM)	g	1.39E-04
			Hydrocarbons (HC)	g	3.24E-04
			Methane (CH_4)	g	7.78E-06
			Benzene (C_2H_6)	g	6.16E-06
			Toluene (C_7H_8)	g	2.59E-06
			Xylene (C_8H_{10})	g	2.59E-06
			Non – methane volatile organic compounds (NMVOCs)	g	9.93E-04
			Sulfur oxides (SO_x)	g	1.43E-04
			Nitrous Oxide (N_2O)	g	2.57E-05
			Cadmium	g	2.04E-09
			Copper	g	3.47E-07
			Chromium	g	1.02E-08
			Nickel	g	1.43E-08
			Selenium	g	2.04E-09
			Zinc	g	2.04E-07
			Lead	g	2.25E-11
			Mercury	g	4.09E-12

4.1.4.2 PLA Product

4.1.4.2.1 Landfill Without Energy Recovery

In landfill, PLA would begin to biodegrade after 11 months at 25°C in water (Bohlmann, 2004). In anaerobic environment, biodegradation of PLA could generate methane. Based on Bohhmann (2004), all PLA was converted to methane in the landfill, but 10% of methane is either chemically oxidized or converted by bacteria to carbon dioxide. The results of the inventory analysis of landfill scenario based on one kg of bioplastic waste are shown in Table 4.14 and Table 4.15.

Table 4.14 Results of the inventory analysis of landfill scenario (without energy recovery) based on one kg of PLA bioplastic wast

Landfill scenario (without energy recovery)					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			**Emissions to Air**		
Bioplastic waste	kg	1.00	CO	g	9.90E-02
Diesel	kg	5.13E-03	CO_2 (fossil)	g	16.34
Electricity	kWh	2.25E-03	CH_4	g	2.20E-02
Tap water	kg	4.93E-03	NO_x	g	0.33
Wire	kg	1.64E-03	N_2O	g	4.00E-04
			SO_x	g	2.70E-02
			CH_4 (biogenic)	g	600
			Emissions to Water		
			BOD	g	6.58E-02
			COD	g	0.11

Table 4.15 Results of the inventory analysis of landfill scenario (with energy recovery) based on one kg of PLA bioplastic waste

Landfill scenario (with energy recovery)					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			Product		
Bioplastic waste	kg	1.00	Electricity	kWh	1.50
Diesel	kg	5.13E-03	**Emissions to Air**		
Electricity	kWh	2.25E-03	CO	g	9.90E-02
Tap water	kg	4.93E-03	CO_2 (fossil)	g	16.34
Wire	kg	1.64E-03	CH_4	g	2.20E-02
			NO_x	g	0.33
			N_2O	g	4.00E-04
			SO_x	g	2.70E-02
			CH_4 (biogenic)	g	300
			Emissions to Water		
			BOD	g	6.58E-02
			COD	g	0.11

4.1.4.2.2 Recycling

For recycling scenario, back- to monomer (BTM) recycling of PLA was considered in this study. About 90% of PLA can be recovered by hydrolysis at 250°C and a processing time of 10 – 20 min (Dornburg *et al.*, 2006).

The energy consumption for separation is 2.1 MJ per kg recycled plastic. Water consumption is 0.005 m^3 per kg recycled plastic (Molgaard, 1995). Table 4.16 shows the results of the inventory analysis of recycling scenario based on one kg of bioplastic waste.

Table 4.16 Results of the inventory analysis of recycling scenario based on one kg of PLA bioplastic waste

Recycling scenario					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			***Product***		
Bioplastic waste	kg	1.00	PLA resin	kg	0.81
Water	m^3	5.00E-03	***Emission to Air***		
Utilities			CO_2	kg	0.33
Electricity	MJ	2.10	***Solid Waste***		
			Plastic waste	kg	0.19

4.1.4.2.3 Composting

Composting is a process at which compostable materials under well controlled circumstances and aerobic condition (presence of oxygen), by means of microorganism, are converted and decomposed. The data used for composting received from the composting plant at Phang, Chiangmai Province. Table 4.17 shows the results of the inventory analysis of composting scenario based on one kg of bioplastic waste.

Table 4.17 Results of the inventory analysis of composting scenario based on one kg of bioplastic (PLA) waste

Composting scenario					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			***Product***		
Bioplastic waste	kg	1.00	Soil container	kg	0.13
Electricity	kWh	6.00E-04	***Emissions to Air***		
Water	l	8.20E-03	CO_2 (fossil)	kg	6.89E-06
Diesel	kg	2.55E-05	CO	kg	4.96E-07
			CH_4	kg	1.10E-07
			NO_x	kg	1.63E-06
			SO_x	kg	2.18E-09
			CO_2 (biogenic)	kg	1.41

4.1.4.2.4 Incineration

- Incineration with energy recovery

Incineration is a process that combusted the waste to generate electricity. Electricity production was calculated with a lower heating value of PLA and electric efficiency of waste incineration plant was estimated to be about 30% (Dornburg *et al.*, 2006). Table 4.18 shows the results of the inventory analysis of incineration scenario based on one kg of bioplastic product.

- Open Burning

Incineration is the thermal destruction of waste. The data used for incineration extracted from final report "Solid waste management holistic decision modeling" (NIPPON, 2008). Table 4.19 shows the results of the inventory analysis of incineration scenario (open burning) based on one kg of bioplastic waste.

Table 4.18 Results of the inventory analysis of incineration with energy recovery scenario based on one kg of bioplastic (PLA) product

Incineration scenario					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			***Products***		
Bioplastic product	kg	1.00	Electricity	kWh	1.50
HCl 35%	l	3.60E-05			
NaOH 50%	l	3.70E-05	***Emission to Air***		
Lime	kg	4.66E-03	CO_2 (biotic)	kg	1.80
Electricity	kWh	4.29E-02	CH_4 (biotic)	kg	2.00E-04
Diesel	kg	1.85E-04	N_20 (biotic)	kg	6.00E-05
Water	kg	2.54E-03	NO_x	kg	8.00E-04
Lubricating oil	kg	1.90E-05	CO	kg	2.50E-04
			SO_x	kg	2.00E-05
			CH_4	kg	1.98E-03
			Emissionto Soil		
			Ash	kg	0.01
			Emission to Water		
			Wastewater	kg	0.02

Table 4.19 Results of the inventory analysis of incineration (open burning) scenario based on one kg of bioplastic (PLA) product

Incineration scenario (open burning)					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			***Emissions to Air***		
Bioplastic waste	kg	1.00	PM	g	7.92
			SO_X	g	0.49
			NO_X	g	2.97
			CO	g	42.06
			CO_2	g	455.06
			CH_4	g	6.43
			Emissions to Soil		
			Ash	kg	0.01

4.1.4.3 PBS Product

4.1.4.3.1 Landfill

Similar to PLA, biodegradation of PBS could generate methane. All PBS was converted to methane in the landfill, but 10% of methane is either chemically oxidized or converted by bacteria to carbon dioxide. In case of landfill with energy recovery, 45% of methane generated was recovered and combusted to generate electricity and the other 45% escaped to the atmosphere. The results of the inventory analysis of landfill scenario based on one kg of bioplastic waste are shown in Table 4.20 – 4.21.

Table 4.20 Results of the inventory analysis of landfill scenario (without energy recovery) based on one kg of PBS bioplastic waste

Landfill scenario (without energy recovery)					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			**Emissions to Air**		
Bioplastic waste	kg	1.00	CO	g	9.90E-02
Diesel	kg	5.13E-03	CO_2 (fossil)	g	16.34
Electricity	kWh	2.25E-03	CH_4	g	2.20E-02
Tap water	kg	4.93E-03	NO_x	g	3.27E-01
Wire	kg	1.64E-03	N_2O	g	4.00E-04
			SO_x	g	2.70E-02
			CH_4 (biogenic)	g	669.31
			Emissions to Water		
			BOD	g	6.58E-02
			COD	g	0.11

Table 4.21 Results of the inventory analysis of landfill scenario (with energy recovery) based on one kg of PBS bioplastic waste

Landfill scenario (with energy recovery)					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			Product		
Bioplastic waste	kg	1.00	Electricity	kWh	1.50
Diesel	kg	5.13E-03	**Emissions to Air**		
Electricity	kWh	2.25E-03	CO	g	9.90E-02
Tap water	kg	4.93E-03	CO_2 (fossil)	g	16.34
Wire	kg	1.64E-03	CH_4	g	2.20E-02
			NO_x	g	3.27E-01
			N_2O	g	4.00E-04
			SO_x	g	2.70E-02
			CH_4 (biogenic)	g	334.66
			Emissions to Water		
			BOD	g	6.58E-02
			COD	g	0.11

4.1.4.3.2 Recycling

For PBS recycling, we have not found data from literature review.

4.1.4.3.3 Composting

Table 4.22 shows the results of the inventory analysis of composting technology based on one kg of bioplastic (PBS) product.

Table 4.22 Results of the inventory analysis of composting scenario based on one kg of bioplastic (PBS) waste

Composting scenario					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			***Product***		
Bioplastic waste	kg	1.00	Soil container	kg	0.13
Electricity	kWh	6.00E-04	***Emissions to Air***		
Water	l	8.20E-03	CO_2 (fossil)	kg	6.89E-06
Diesel	kg	2.55E-05	CO	kg	4.96E-07
			CH_4	kg	1.10E-07
			NO_x	kg	1.63E-06
			SO_x	kg	2.18E-09
			CO_2	kg	0.84

4.1.4.3.4 Incineration

Incineration is a process that combusted the waste to generate electricity. Electricity production was calculated with a lower heating value of PLA and electric efficiency of waste incineration plant was estimated to be about 30% (Dornburg *et al.*, 2006). Table 4.23 shows the results of the inventory analysis of incineration scenario based on one kg of bioplastic (PBS) product.

Table 4.23 Results of the inventory analysis of incineration with energy recovery scenario based on one kg of bioplastic (PBS) product

Incineration scenario					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources			***Products***		
Bioplastic product	kg	1.00	Electricity	kWh	1.50
HCl 35%	l	3.60E-05			
NaOH 50%	l	3.70E-05	***Emission to Air***		
Lime	kg	4.66E-03	CO_2 (biotic)	kg	1.08
Electricity	kWh	4.29E-02	CO_2 (abiotic)	kg	0.96
Diesel	kg	1.85E-04	CH_4 (biotic)	kg	2.00E-04
Water	kg	2.54E-03	N_20 (biotic)	kg	6.00E-05
Lubricating oil	kg	1.90E-05	NO_x	kg	8.00E-04
			CO	kg	2.50E-04
			SO_x	kg	2.00E-05
			CH_4	kg	1.98E-03
			Emissionto Soil		
			Ash	kg	0.01
			Emission to Water		
			Wastewater	kg	0.02

4.2 Life Cycle Impact Assessment

4.2.1 Cradle to Gate (Resin Production)

4.2.1.1 PLA Resin Production

After LCI for PLA resin production was completed, life cycle impact assessment (LCIA) could be analyzed for one kilogram of PLA resin for the relevant impact categories, using both impact assessment model CML 2 baseline 2000 and Eco-Indicator 95. However, only the LCIA results using CML method are shown in this chapter whereas the results using Eco-Indicator method are included in Appendix B. Figure 4.9 illustrates a simple process diagram of Cassava-based PLA resin production, which can be divided into 4 main unit processes: cassava roots

production, starch production, sugar production and PLA resin production. The PLA resin production is based on PURAC's inventory data which includes lactic acid production, and polymerization process. Figure 4.10 shows the greenhouse gas (GHG) emission in each unit process per kg of Cassava-based PLA resin. It can be seen from this figure that the resin production process has the highest GHG impact among the four unit process of the overall PLA resin production.

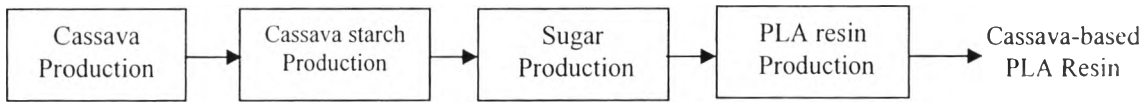


Figure 4.9 A simple process diagram of Cassava-based PLA resin production.

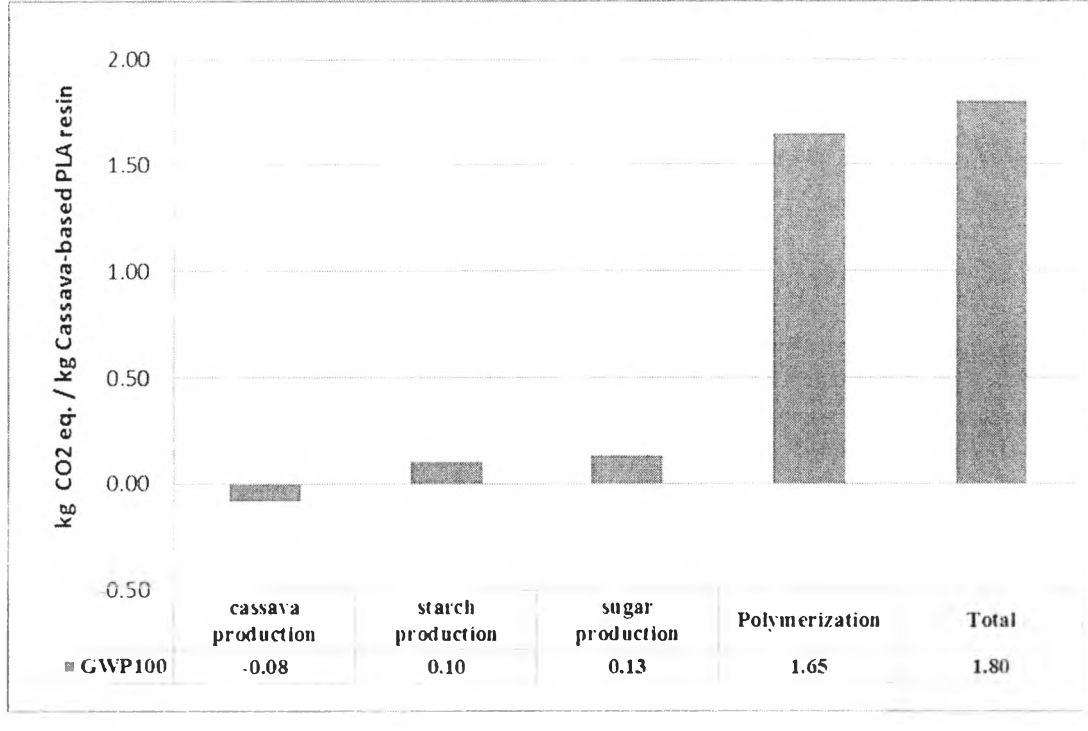


Figure 4.10 GHG emission of Cassava-based PLA resin production for each unit process by using CML 2 baseline 2000.

- Global Warming Potential (GWP)

GWP impact is represented by GHG emission as shown in Figure 4.10. From the figure, it can be seen that the net GHG emission for cassava-based PLA resin production is 1.80 kg CO_2 eq./kg resin. The major CO_2 emission (about 95%) comes from polymerization process due to energy consumption, including steam and electricity. Other parts of emissions come from sugar and starch production. In this aspect, the utilization of biogas from wastewater treatment from cassava production has been proposed as an improvement option to help reduce GWP. It is found that the net GHG can be reduced to 1.47 kg CO_2 eq./ PLA resin or about 18%.

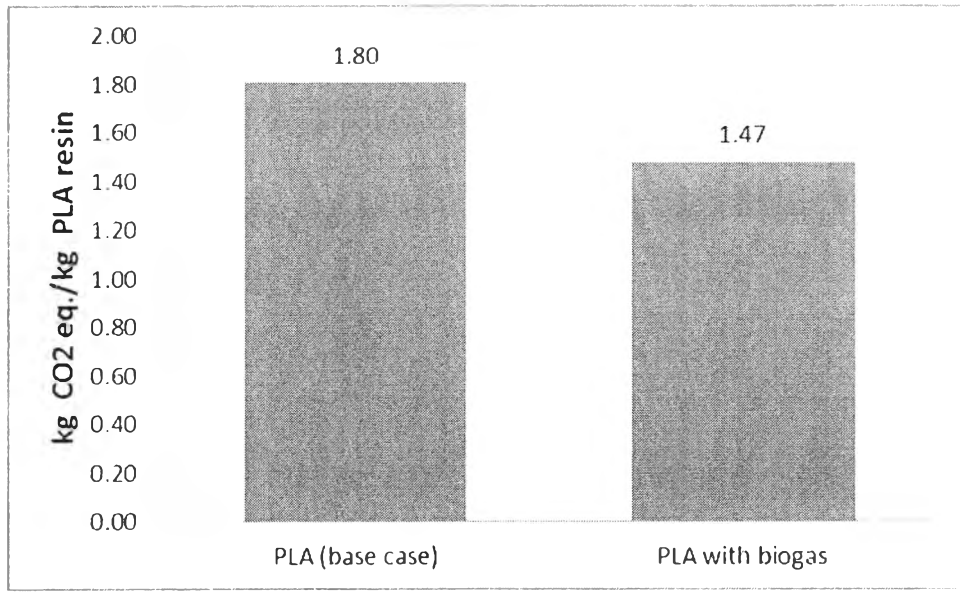


Figure 4.11 Comparison of GWP between Cassava-based PLA resin (base case) and PLA with biogas by using CML 2 baseline 2000.

4.2.1.2 PBS Resin Production

Similar to PLA, after LCI for PBS resin production was completed, life cycle impact assessment (LCIA) could be analyzed for one kilogram of PBS resin for the relevant impact categories using both CML 2 baseline 2000 and Eco Indicator 95. In this part, we divided into two types of PBS: PBS-1 is produced form bio-based succinic acid (SA) and 1, 4-butanediol (BDO) produced from

petroleum (petroleum-based) and PBS-2 is produced from both bio-based SA and bio-based BDO. Figure 4.12 shows the unit processes involved in the life cycle of PBS-1 resin production. It can be seen that the resources for PBS-1 production come from both biomass and fossil as succinic acid is produced from sugar whereas BDO is produced from petroleum. Figure 4.13 shows the unit processes of PBS-2 resin production which produced from both bio-based SA and bio-based BDO. Figure 4.14 shows the LCIA results of GWP of PBS-1 resin in various stages throughout its life cycle.

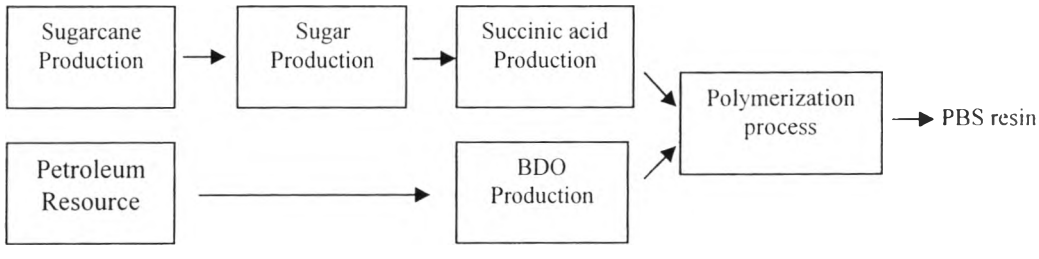


Figure 4.12 A simple process flow diagram of PBS-1 resin production.

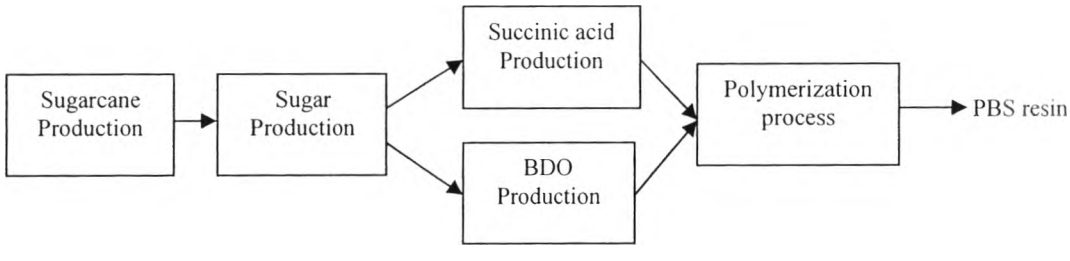


Figure 4.13 A simple process flow diagram of PBS-2 resin production.

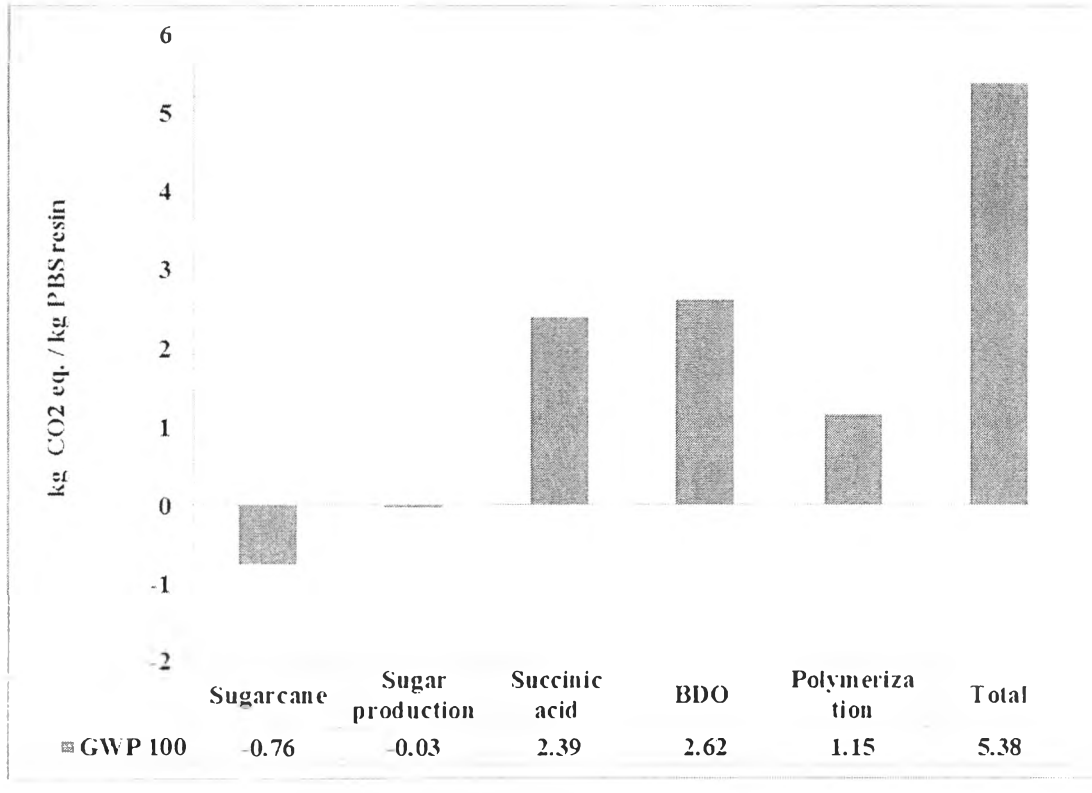


Figure 4.14 GWP of PBS-1 resin in various life cycle stages by using CML 2 baseline 2000.

From Figure, it can be seen that succinic and BDO production contribute significantly to the GWP of PBS-1 resin followed by polymerization process. The total GWP of PBS-1 resin production is shown to be 5.38 kg CO_2 eq. of which the highest amount of about 50% comes from BDO (2.61 kg CO_2 eq.) due to its petroleum originality. The second highest contribution is from succinic production where about 70% comes from energy consumption, including steam and electricity from natural gas and about 25% from the use of ammonia. It can also be noticed from Fig.4.14 that the GWP values for sugarcane and sugar production are negative because of the carbon offset by CO_2 uptake of sugarcane and surplus electricity production from bagasse in the sugar plant. As a result, the net GHG emission for succinic production (cradle-to-gate) is reduced to only 1.6109 kg CO_2 eq.

The comparison of GWP between PBS resin, Cassava-based PLA resin and Polyethylene (PE) resin is shown in Figure 4.15. From this figure, it

can be seen that GHG emission from PBS-1 has shown to be the highest but it has significantly decreased when it is produced from bio-based SA and bio-based BDO (PBS-2), the GWP can be decreased around 24%. For PLA, GHG impact from Cassava-based PLA resin with biogas has shown to be the lowest.

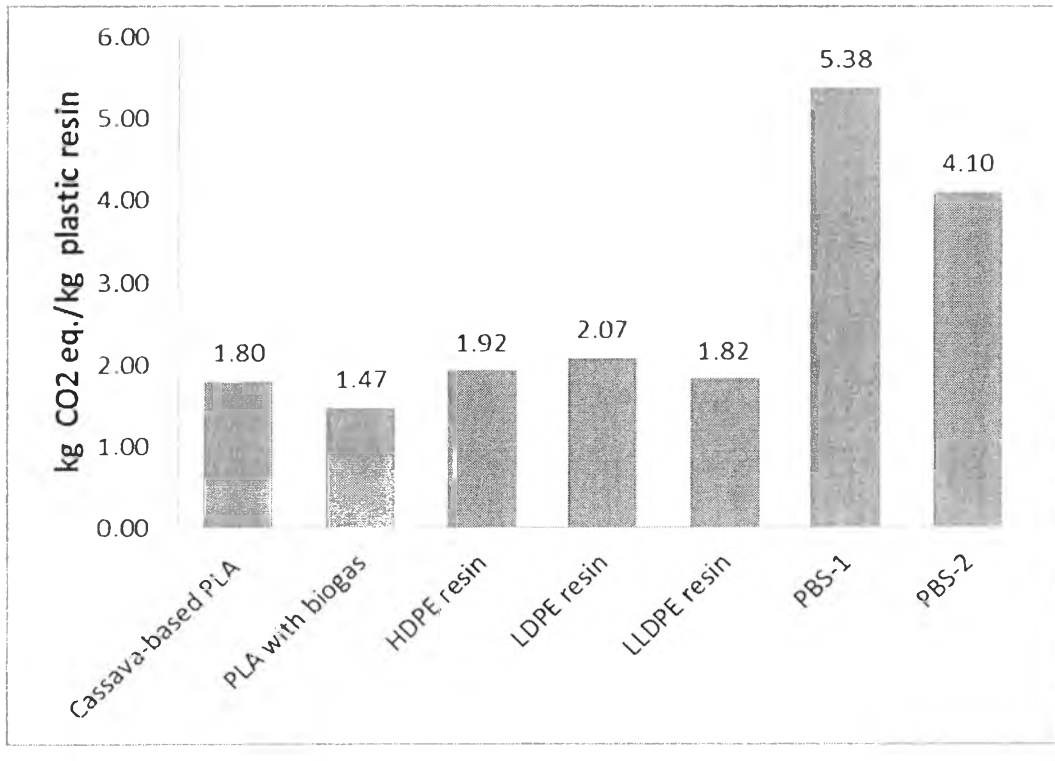


Figure 4.15 Comparison of GWP of bioplastic and conventional plastic resins by using CML 2 baseline 2000.

4.2.1.3 Other Impact Categories of Bioplastic and Conventional Plastic Resin

In this part, only PLA with biogas was considered for various impact categories.

4.2.1.3.1 Acidification

From the figure, it can be seen that PBS-1 has shown to be the highest acidification which is equal to 2.39E-02 kg SO_2 eq./kg of

resin. The lowest acidification is LLDPE which is equal to 5.71E-03 kg SO_2 eq./kg of resin. In case of PLA, it was also higher acidification than conventional resin.

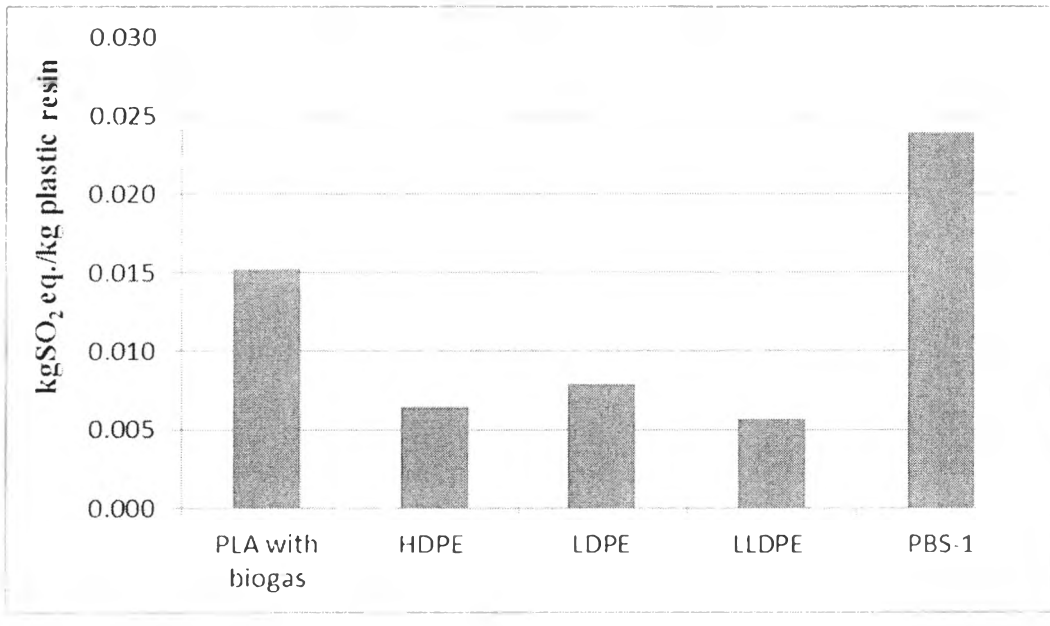


Figure 4.16 Comparison of acidification of bioplastic and conventional plastic resins by using CML 2 baseline 2000.

4.2.1.3.2 Eutrophication

From figure 4.17, it can be seen that PBS-1 has shown to be the highest eutrophication which is equal to 1.46E-03 kg PO_4^- eq./kg of resin. The lowest eutrophication is LLDPE which is equal to 4.45E-04 kg PO_4^- eq./kg of resin. For PLA has shown the eutrophication 1.29E-03 kg PO_4^- eq./kg of resin.

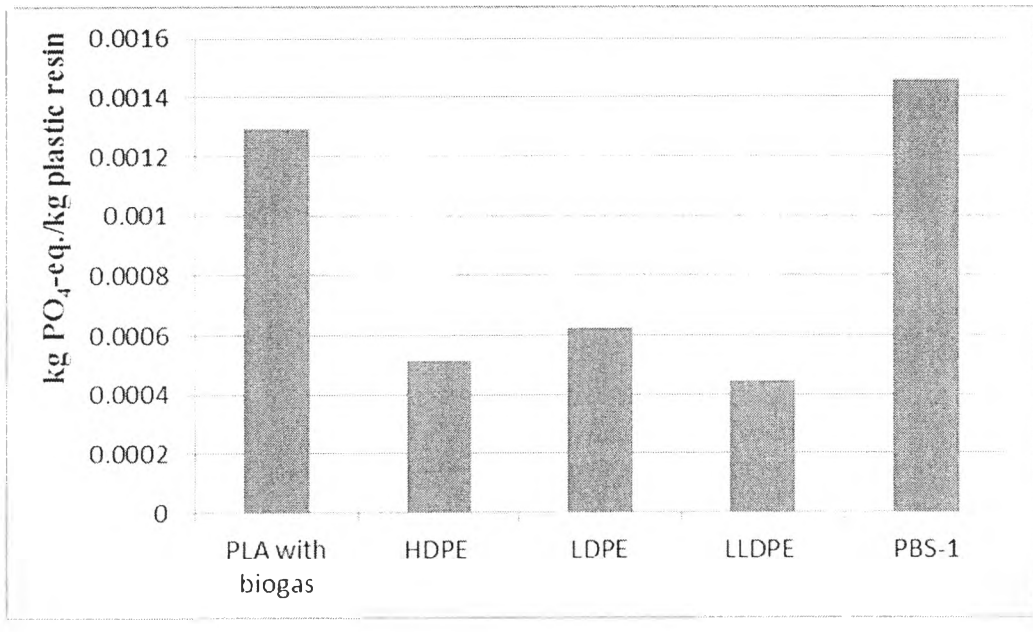


Figure 4.17 Comparison of eutrophication of bioplastic and conventional plastic resins by using CML 2 baseline 2000.

4.2.1.3.3 Abiotic Depletion

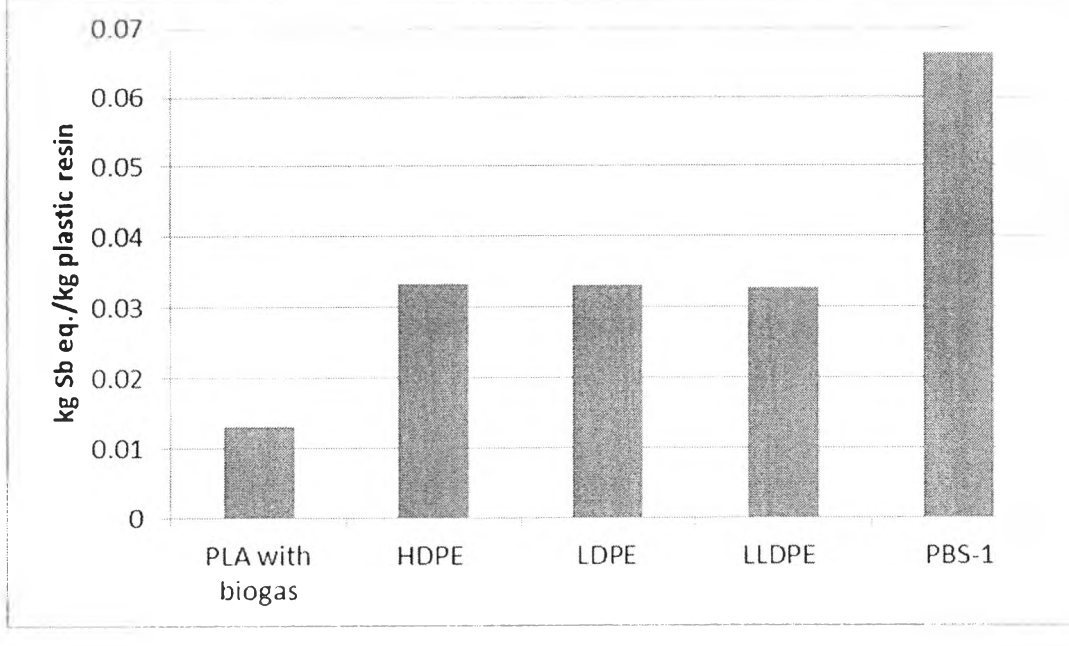


Figure 4.18 Comparison of abiotic depletion of bioplastic and conventional plastic resins by using CML 2 baseline 2000.

From figure 4.18, it can be seen that PBS-1 has shown to be the highest abiotic depletion which is equal to 6.63E-02 kg Sb eq./kg of resin. The lowest abiotic depletion is PLA which is equal to 1.31E-02 kg Sb eq./kg of resin which is lower than conventional resins.

4.2.1.3.4 Energy Resources

The data for energy resources were taken from Eco-Indicator 95 method.

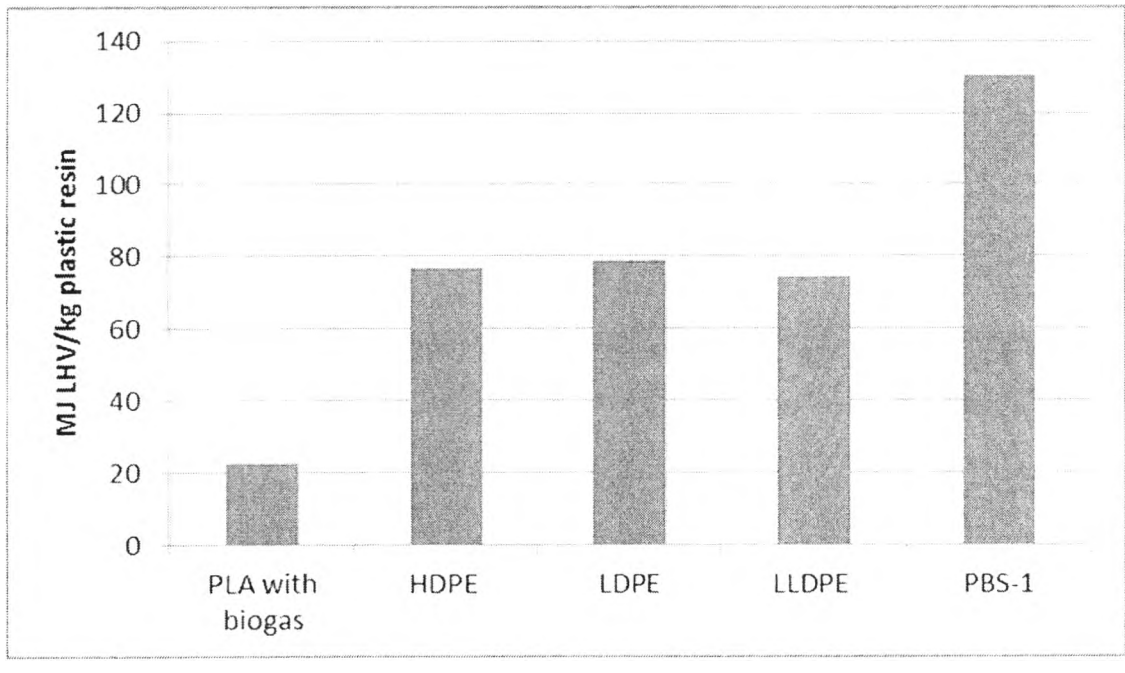


Figure 4.19 Comparison of energy resources of bioplastic and conventional plastic resins by using CML 2 baseline 2000.

From figure 4.19, it can be seen that PBS-1 has shown to be the highest energy resources which is equal to 130.37 MJ LHV/kg of resin while PLA has the lowest energy resources which is equal to 24.13 MJ LHV/kg of resin.

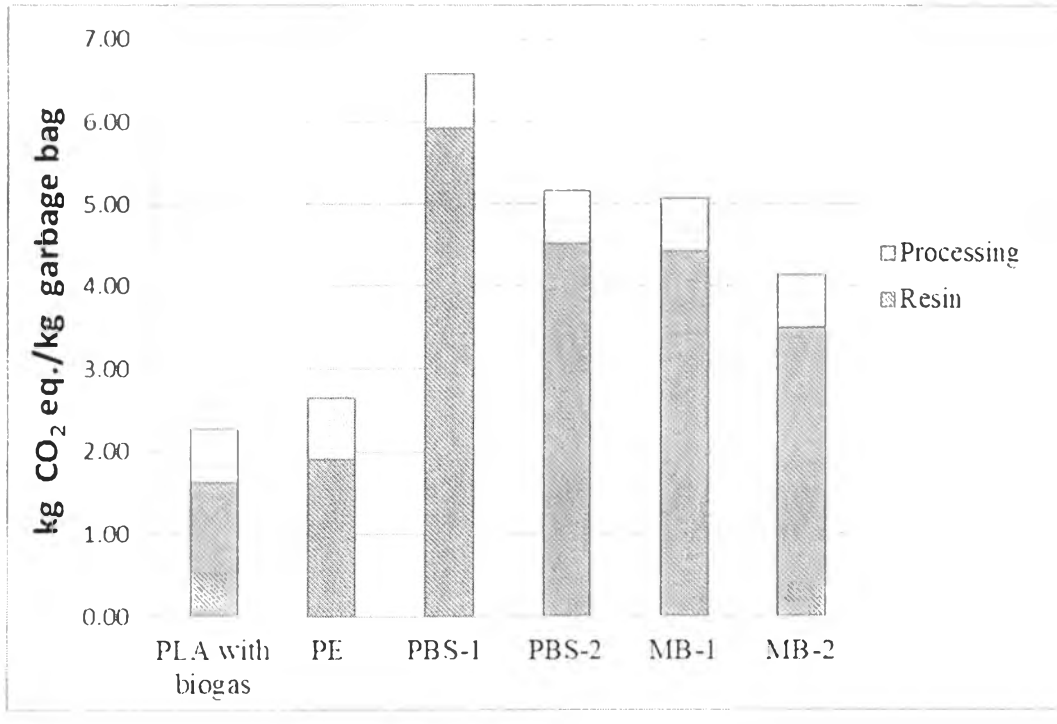
4.2.2 Bioplastic Product

In this part, LCIA was conducted for bioplastic product based on cradle-to-gate approach, which includes bioplastic resin production, transportation of resin to plastic processing factory, and the processing of the bioplastic product. Garbage bag was selected as a model product to study. In this study, two bioplastics (PLA and PBS) were mixed in the ratio 65% PBS and 35% PLA which based on the real number that used in manufacturer to improve mechanical properties of bioplastic. The environmental performance was then compared with the same product produced from conventional plastics (HDPE, LDPE, LLDPE) based on one kg of plastic product.

4.2.2.1 Environmental Impacts of Bioplastic Product (Garbage Bag)

4.2.2.1.1 Global Warming Potential

From figure 4.20, it can be seen that the most GWP impact of garbage bag comes from resin production and for product processing the main of GWP comes from electricity use in the plastic production. When compared with the same product that produced from PE, PLA has lower GWP which is distribute GWP 2.27 kg CO_2 eq./kg garbage bag. For PBS garbage bag, it has the highest GWP which is due to the PBS resin as shown in previous section (Fig.4.15). For mixed bioplastics 1 and 2 the GWP are still higher than product which produced from conventional plastic but this impact can be reduced by applied suitable waste treatment.



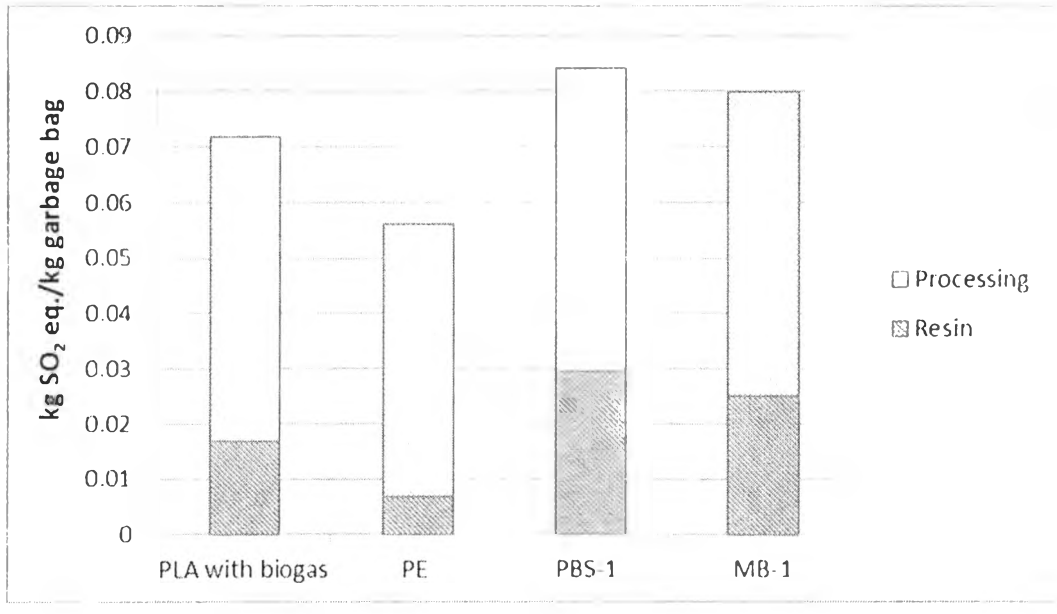
Note: *MB-1 is mixed bioplastics 1 which consist of 65% PBS-1 and 35% PLA*

MB-2 is mixed bioplastics 2 which consist of 65% PBS-2 and 35% PLA

Figure 4.20 Comparison of GWP of bioplastic and conventional plastic product (garbage bag) by using CML 2 baseline 2000.

4.2.2.1.2 Acidification

From the figure below, it can be seen that the most acidification comes from plastic processing with includes transportation. When investigated into details the main acidification comes from transportation of resin. From the figure, PBS-1 has shown to be the highest acidification which is equal to 8.42E-02 kg SO_2 eq./kg of garbage bag. Garbage bag produced PE has the lowest acidification which is equal to 5.61E-02 kg SO_2 eq./kg of garbage bag. In case of PLA, it was also higher acidification than conventional plastic.

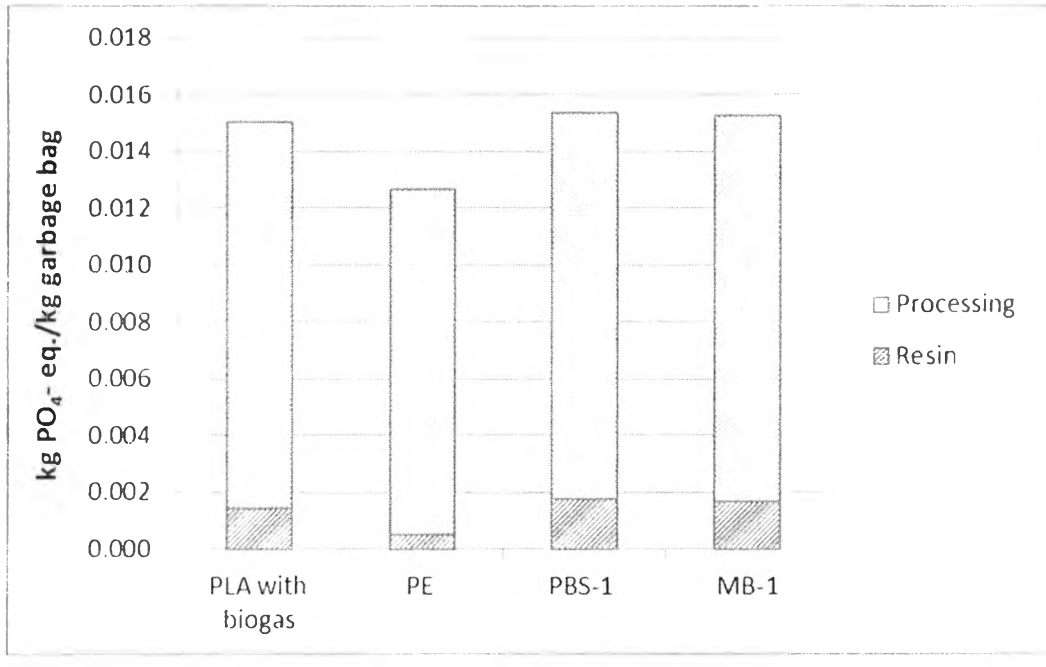


Note: MB-1 is mixed bioplastics 1 which consist of 65% PBS-1 and 35% PLA

Figure 4.21 Comparison of acidification of bioplastic and conventional plastic product (garbage bag) by using CML 2 baseline 2000.

4.2.2.1.3 Eutrophication

From the figure 4.22, it can be seen that the most eutrophication comes from plastic processing with includes transportation. Similar explanation to acidification impact, when investigated into details the main eutrophication comes from transportation of resin. And from the figure, garbage bag from PBS-1 has shown to be slightly higher than PLA and both of them were higher eutrophication than garbage bag from conventional plastic.

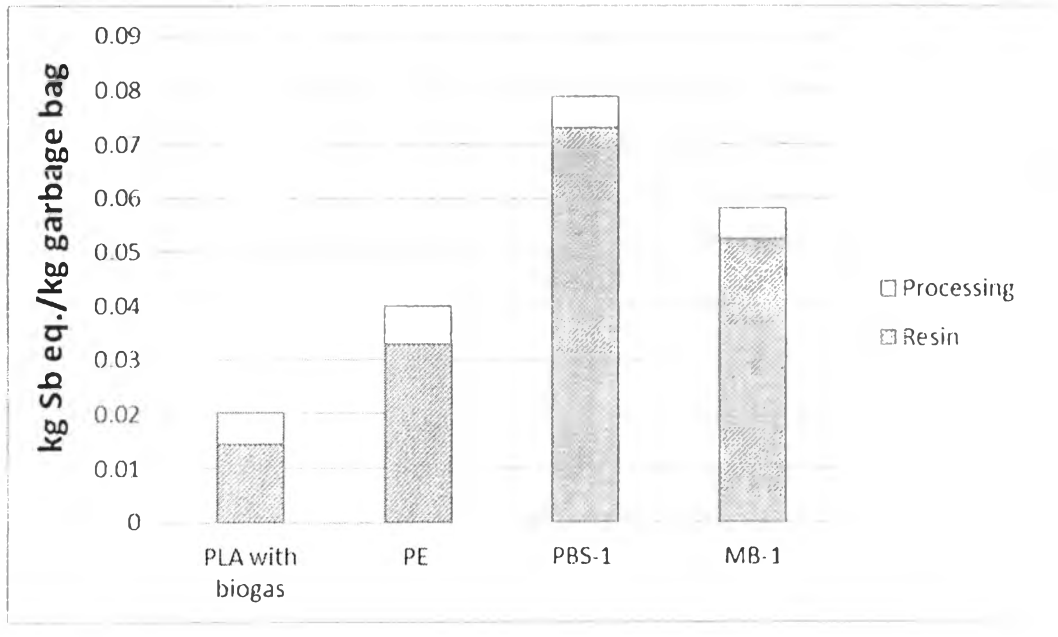


Note: MB-1 is mixed bioplastics 1 which consist of 65% PBS-1 and 35% PLA

Figure 4.22 Comparison of eutrophication of bioplastic and conventional plastic product (garbage bag) by using CML 2 baseline 2000.

4.2.2.1.4 Abiotic Depletion

From the figure 4.23, it can be seen that the most abiotic depletion comes from resin production and for product processing the main of GWP comes from electricity use in the plastic processing. And from the figure, PBS-1 has shown to be the highest abiotic depletion which is equal to 7.86E-02 kg Sb eq./kg of garbage bag. Garbage bag produced PLA has the lowest acidification which is equal to 0.02 kg Sb eq./kg of garbage bag.

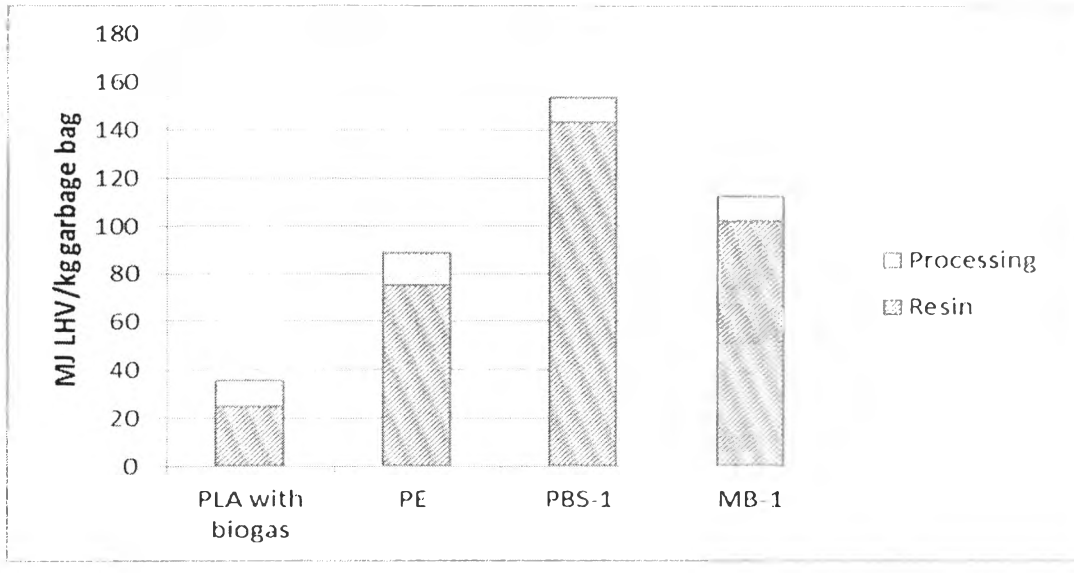


Note: MB-1 is mixed bioplastics 1 which consist of 65% PBS-1 and 35% PLA

Figure 4.23 Comparison of abiotic depletion of bioplastic and conventional plastic product (garbage bag) by using CML 2 baseline 2000.

4.2.2.1.5 Energy Resources

The data for energy resources were taken from Eco-Indicator 95 method. From figure 4.24, it can be seen that PBS-1 has shown to be the highest energy resources which is equal to 153.88 MJ LHV/kg of garbage bag while PLA has the lowest energy resources which is equal to 35.47 MJ LHV/kg of garbage bag.



Note: MB-1 is mixed bioplastics 1 which consist of 65% PBS-1 and 35% PLA

Figure 4.24 Comparison of energy resources of bioplastic and conventional plastic product (garbage bag) by using CML 2 baseline 2000.

4.2.3 Disposal Phase

In this part, only disposal phase of the bioplastic products was analyzed and presented. Four disposal technologies: landfill (with and without energy recovery) recycling, composting and incineration were used in this study as a means to treat bioplastic wastes in order to assess the environmental impacts of the disposal phase of the bioplastic wastes and to determine the suitable waste management scheme for bioplastics. The basis for the analysis in this part is to treat 1 kg of 100% PLA or PBS plastic waste.

4.2.3.1 PLA Product

Figure 4.25 shows GWP of the four disposal technologies based on 1 kg PLA waste being treated. Each disposal technology is discussed below.

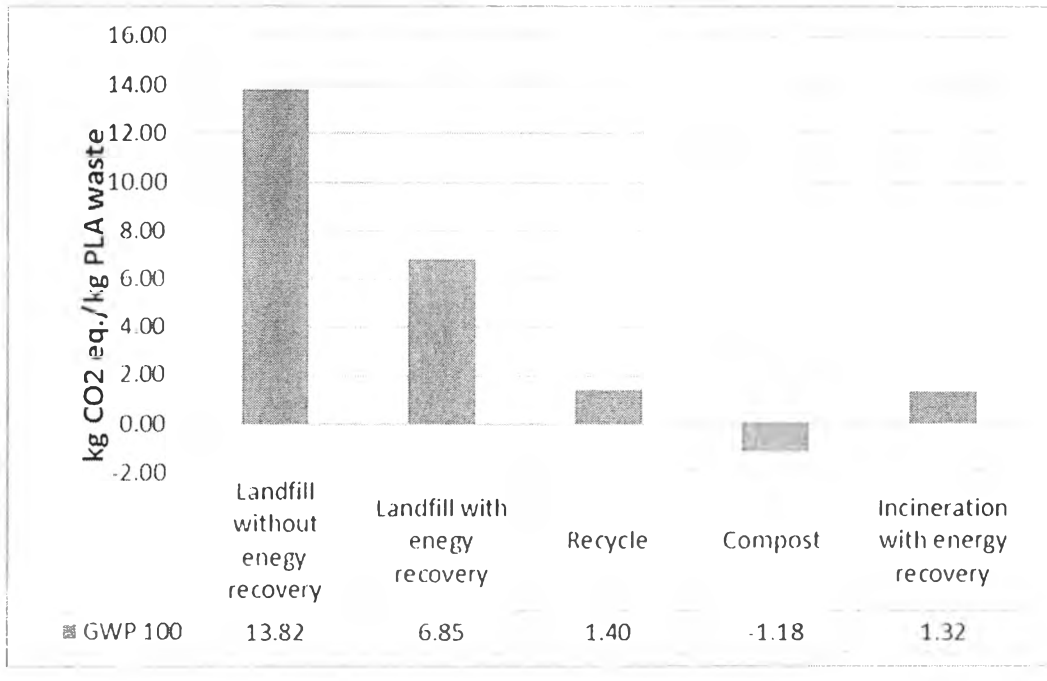


Figure 4.25 GWP of various disposal technologies based on 1 kg PLA product treated by using CML 2 base line 2000.

Landfill

From Figure 4.25, the GWP of landfill without energy recovery is 13.82 kg CO_2 eq. per kg PLA treated. The largest amount of GHG generated from landfill was a result of the degradation of PLA under anaerobic condition in the landfill site which emitted large amount of methane (90% CH_4) and carbon dioxide (10% CO_2) to the atmosphere (carbon neutral). Furthermore, the use of diesel during the collection of bioplastic waste and electricity during baling process caused the second and the third highest contribution to the GWP impacts, respectively. As a result, the GWP of this treatment technology is shown to be highest among all treatment technologies studied.

In case of landfill with energy recovery, 45% of methane generated was collected (recovered) through pipeline buried underneath the landfill site and sent to gas engine and generator in order to generate electricity whereas the other 45% of methane was estimated to escape to the atmosphere. The energy recovered is estimated to be equal to electricity of 1.55 kWh, which is

supplied to the EGAT grid-mix. This helps reduce the need to produce equal amount of electricity and it is considered to reduce the environmental impact by compensating the environmental impact resulting from electricity production of EGAT. Thus, the total GWP for landfill with energy recovery was decreased to 6.85 kg CO_2 eq./kg PLA treated as shown in Fig.4.25.

Recycling

The recycling process used in this study is based on literature review where PLA waste is recycled back to lactic acid (L-LA) and then polymerized to PLA resin again. From the assessment, the total GWP of recycling PLA waste was found to be 3.25 kg CO_2 eq./kg PLA treated. However, as the recycled PLA is finally converted into the virgin resin, this recycling activity leads to a reduction of need to produce virgin PLA resin of the equal amount. Thus, the total GWP of recycling PLA waste should be deducted by the GWP of the production of virgin PLA resin (1.85 kg CO_2 eq. per kg PLA). As a result, the net GWP for recycling PLA waste was shown to be 1.40 kg CO_2 eq. per kg PLA treated.

Composting

For composting, the bioplastic wastes are degraded under aerobic conditions which results in soil containing substance and emission of CO_2. As PLA is produced totally from renewable resources, the CO_2 emitted is considered carbon neutral in this study (not counted as GHG emission). The soil containing substance from the composting process is usually mixed with animal manure and utilized as fertilizer which can replace the use of chemical fertilizer. Thus, the total GWP of the composting process should be compensated by the GWP of chemical fertilizer production. As a result, the net GWP of composting technology is -1.18 kg CO_2 eq./kg PLA treated. As shown in Fig.4.25, it should be noted that the GWP of the composting treatment for PLA waste is shown to be the lowest among all treatment technologies studied.

Incineration

When PLA wastes are treated by incineration, they are recovered as energy. The remaining part from the combustion of plastics is ash which is required to be treated by landfill. The energy as estimated from their LHV is utilized to generate electricity. The electricity generated is considered as a compensation for the grid-mix electricity, and thus, the GHG of grid-mix electricity of EGAT is used to subtract from the total GHG emission of the incineration process. Consequently, the net GWP of incineration technology is 1.32 kg CO_2 eq. per kg PLA treated as shown in Figure 4.25.

4.2.3.2 PBS Product

Similar analysis to PLA was used to assess the environmental impact of the waste treatment for PBS as well as the waste management scenarios. For PBS, only three disposal technologies, landfill; composting; and incineration, were studied since recycle of PBS has not been reported anywhere. In order to evaluate the suitable waste management for treating PBS waste, it should be noted that PBS is made of succinic acid and BDO which are produced from renewable and fossil resources, respectively. Owing to this fact, the environmental assessment for PBS is analyzed a bit different compared to PLA. However, this study considers PBS to be totally biodegradable. Figure 4.26 shows GWP of all three disposal technologies based on 1 kg PBS product.

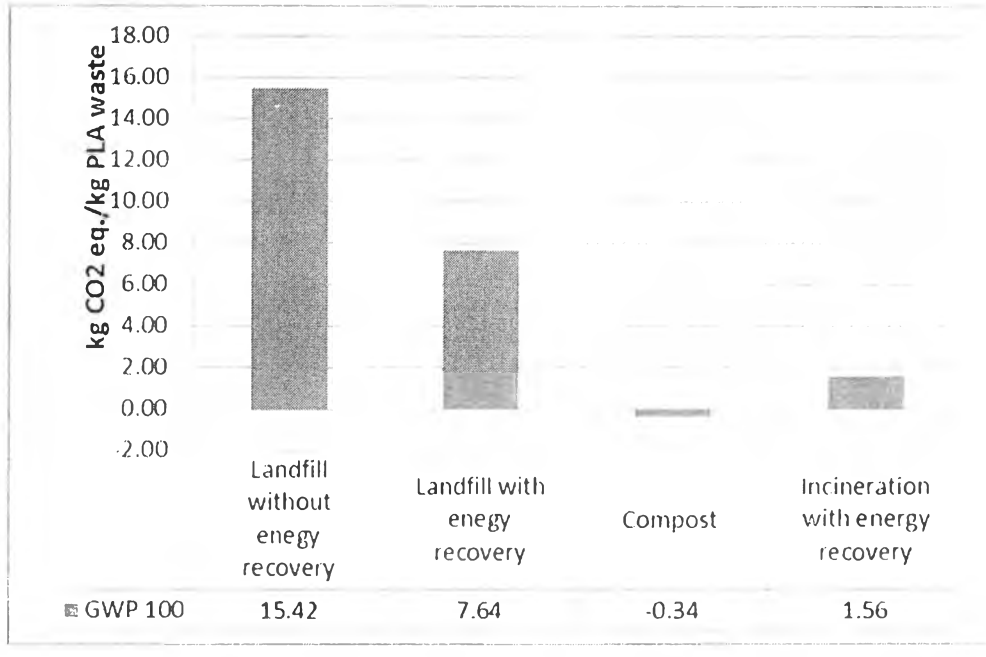


Figure 4.26 GWP of three disposal technologies based on 1 kg PBS product by using CML 2 base line 2000.

Landfill

In this part, we consider PBS to be 100% biodegradable which is the same as PLA. However, as only succinic part of PBS comes from renewable source, only half of CO_2 generated along with CH_4 under anaerobic condition in landfill is then considered carbon neutral. This is different from PLA case where all CO_2 generated is considered carbon neutral. For CH_4, all CH_4 generated from anaerobic digestion is considered potential GWP since it cannot be absorbed biologically by plants.

For landfill without energy recovery, the total GWP is shown to be 15.42 kg CO_2 eq./kg PBS treated. This is highest among all disposal technologies studied which can be attributed to the high generation and release of GHG from landfill process and the use of fossil fuels during collection of waste and landfill operation. In case of landfill with energy recovery, it was assumed that 45% of methane generated could be recovered and sent to gas combustion engine to generate electricity whilst the other 45% CH_4 was not collected/recovered and consequently released to the atmosphere. It is estimated that 1.55 kWh of

electricity was produced and supplied to the grid which is considered to help decrease environmental impact because of the substitution of the electricity from landfill gas to the electricity production of EGAT (Grid-mixed). After the compensation of this electricity, the total GWP is reduced to 7.64 kg CO_2 eq./kg PBS treated. When compared to PLA (Fig.4.25), the GWP of landfill of PBS waste for both cases (with and without energy recovery) is higher than PLA. This is due to the higher carbon content in PBS and the fact that only half of PBS is from renewable resources while PLA is totally from renewable resources.

Composting

Similar analysis to PLA was done for composting PBS, accept the amount of the CO_2 to be considered carbon neutral. Due to the fact that only half of PBS is from renewable resources, half of CO_2 emitted from composting PBS must be treated as potential GHG. As PBS is considered 100% biodegradable same as PLA, the whole PBS wastes are degraded under aerobic conditions and eventually become soil containing substance which can be utilized as fertilizer to help reduce the use of chemical fertilizer. After the compensation of the GWP of organic compost production, the net total GWP of the composting process for PBS wastes is -0.34 kg CO_2 eq./kg PBS treated.

Incineration

In this part, as LHV of PBS could not be found, we assumed the LHV value of PLA to be used for PBS. Therefore, the amount of heat and electricity generated from incineration of PBS is equal those of PLA case. However, as about half of PBS is from fossil resources (BDO), half of CO_2 emitted from combustion of PBS was treated as potential GHG emission. This is the only difference between PLA and PBS in the case of incineration which leads to higher GWP of PBS (0.24 kg CO_2 eq./ kg PBS treated) when compared to PLA (Fig.4.25).

4.3 Comparison of the Environmental Performance Between Bioplastics and Conventional Plastics

In this part, the environmental performance of bioplastics, PLA and PBS, were compared with conventional plastic of the same product. The comparison was divided into 2 parts: comparison of the cradle-to-gate environmental performance of plastic resin and comparison of the cradle-to-grave environmental performance of the product.

4.3.1 Cradle to Gate

Figure 4.27 shows the comparison of the environmental performance in term of GWP between bioplastic resins and conventional plastic resins on a cradle-to-gate approach. HDPE, LDPE, and LLDPE were selected in this study to compare with PLA and PBS based on the end product of interest in this study (garbage bag).

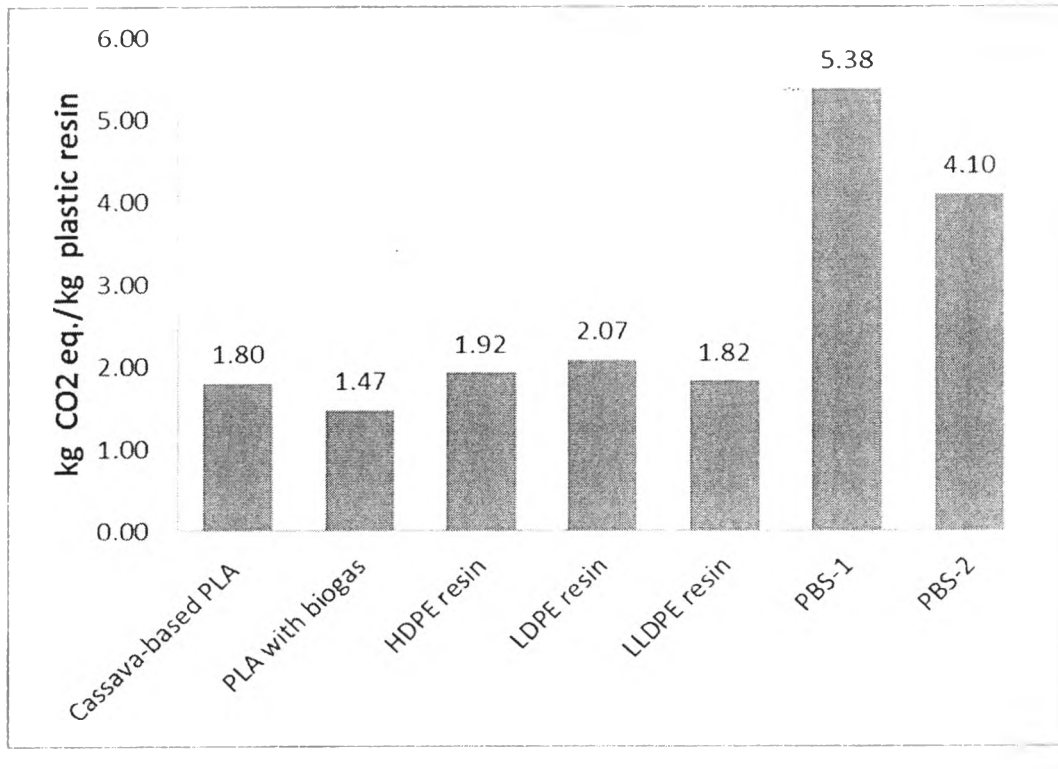


Figure 4.27 Comparison of the environmental performance of plastic resin (cradle-to-gate) based on one kilogram of plastic resin by using CML 2 baseline 2000.

The results show that owing to its half fossil-based in nature (1,4-butanediol or BDO), PBS resin has the highest GWP per weight basis among all resins used in this comparison. However, the impact can be reduced by choosing to produce PBS resin purely from renewable resources (PBS-2). For cassava-based PLA when improvement option (utilization of wastewater from cassava plant to produce biogas for electricity generation) was taken into account, the GWP of cassava-based PLA resin is reduced significantly to 1.47 kg CO_2 eq. per kg resin. This GWP value is the lowest and much lower than GWP of conventional plastic resins (HDPE, LDPE and LLDPE) to be used to produce the same products (garbage bag).

4.3.2 Cradle to Grave

In this part, the life cycle environmental performance of model bioplastic product produced from PLA and PBS were compared with the same product produced from conventional plastics. The comparison based on cradle-to-grave approach covers the production of the resin, processing of the products, and disposal of the products.

Sa-med Island is chosen as a model site to study the management of bioplastic product because it has been set as an experimental site by National Innovation Agency (NIA) to promote the use and proper disposal of bioplastic in Thailand where a model composting plant has been built. The current waste management technologies at Sa-med were landfill without energy recovery, open burning and recycle. For waste management of bioplastic, this study considers that bioplastic garbage bag used to collect only organics waste (about 40 % of total waste) to produce bio-fertilizer at compost plant which has been built by NIA based on technology developed by Suranaree University of Technology. For life cycle impact assessment (LCIA), this study aimed to assess the impact of use of bioplastic bag in reducing the environmental impact of the overall waste management of the model site which is Sa-med island. Therefore, in this part, are focused on comparing the management of ordinary municipal solid waste (MSW) between the current scenario and scenarios with the use of bioplastics. Table 4.24 shows the waste management at Sa-med.

Table 4.24 The current and suitable waste management for Sa-med island

Waste management scenario	Landfill without energy recovery	Incineration	Compost	Recycle
Current scenario	40	40	-	20
Scenario with bioplastic	-	40	40	20

The total waste of Sa-med island consist of organic waste 40%, recyclable waste 20% and other waste 40%. For current scenario at Sa-med, organics waste was treated by landfill without energy recovery, recyclable waste was sent to recycle and other waste was treated by open burning. In case of new technology, bioplastic garbage bag was used to replace conventional garbage bag (partial replacement) in order to collect organic waste and was then treated by composting. The results for waste management are shown in the figure below.

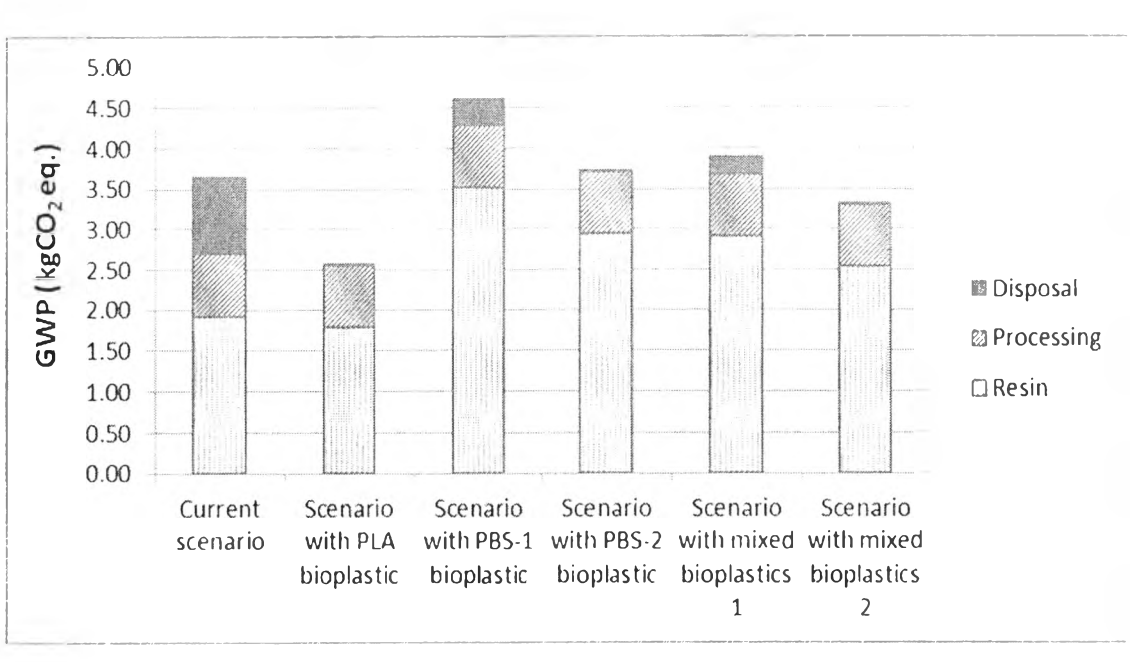


Figure 4.28 Comparison of the environmental performance of plastic product (cradle-to-grave) based on one kilogram of garbage bag by using CML 2 baseline 2000.

The life cycle GWP of PLA and PBS garbage bag for all waste management scenarios are shown in Figure 4.28. From the figure, it can be seen that the main carbon dioxide emissions occur in resin production step. Comparing to the base case where the garbage bag is produced from mixed polyethylene (HDPE, LDPE and LLDPE), the results show that GWP of bioplastic (PLA) bag is lower than that of PE bag. In addition, as PLA and PBS are compostable bioplastics, the soil containing substance from the composting process can be mixed with animal manure and utilized as fertilizer. Thus, the GWP of the composting process should be compensated by the GWP of chemical fertilizer production. As a result, the net GWP of the composting process is -1.18 kg CO_2 eq./kg bioplastics treated. For this reason, scenario with PLA bioplastic has about 29.86% lower in GWP when compared with PLA bag base case (current waste management at Sa-med). The scenarios with PBS-1 and PBS-2 were higher in GWP than base case of 20.94 % and 1.92%, respectively. The scenario with mixed bioplastics 1 was higher in GWP than current scenario of 6.34 % due to the high GWP in resin production step but the scenario with mixed bioplastics 2 was lower in GWP than current scenario 9.18 %. However, this effect should be compensated with the degradation rate of bioplastics which faster than conventional plastics.