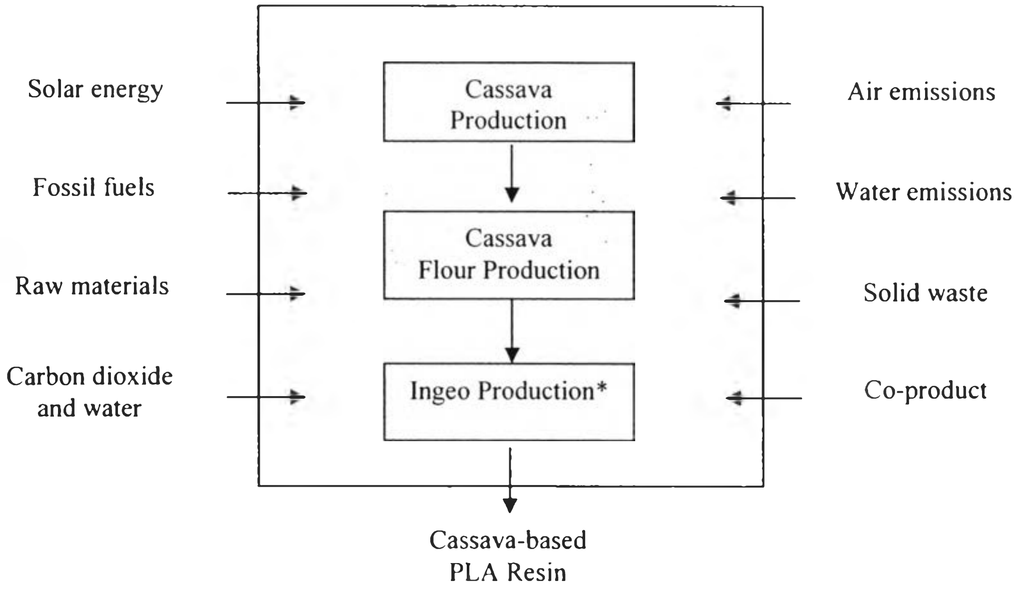
สำนักงานวิทยทรัพยากร จุฬาลงกรณ์มหาวิทยาลัย

CHAPTER IV
RESULTS AND DISCUSSION

4.1 Life Cycle Inventory

4.1.1 PLA Resin Production

As PLA resin is not currently produced in Thailand, the production of PLA resin based on NatureWorks LLC (USA), is used as a base model for this study with a modification that cassava is to be used instead of corn. 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 flour before entering the resin production stage. The final product which is resin is called "Cassava-based PLA Resin".



** Including: Dextrose Production, Lactic Acid Production, and Lactide Production*

Figure 4.1 The production of PLA resin in Thailand.

In this part, the inventory data from Vink *et al.* (2010) were used as the secondary data for the production of PLA resin of NatureWorks (trade name is "Ingeo"). Based on Vink's inventory data, the inventory data for Cassava-based PLA resin were constructed step-by-step in this study. First, the corn production data were carefully taken out from Vink's inventory data based on data from West *et al.* (2002) and Renouf *et al.* (2008) and then replaced by the primary data for cassava production from MTEC and by the secondary data for cassava flour production from Department of Industrial Works (DIW). 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. Table 4.1 shows the inventory analysis of the production of Cassava-based PLA resin. The inventory data for cassava plantation and cassava flour production are included in Appendix A.

Table 4.1 Results of the inventory analysis of one kilogram Cassava-based PLA resin

Input inventory		**Output inventory**	
Type	**Unit**	**Type**	**Unit**
Energy	**MJ**	***Product***	**kg**
Energy, from coal	16.5854	Cassava-based PLA resin	1.00
Energy, from oil	2.7788		
Energy, from gas, natural	18.0720	***Emission to Air***	**mg**
Energy, from hydro power	0.6594	CO	4,883.8424
Energy, from uranium	3.9077	CO_2	2,549,875.468
Energy, from coal, brown	14.0462	SO_x as SO_2	7,563.9198
Energy, from sulfur	0.0718	NO_x as NO_2	12,311.521
Energy, from biomass	111.4005	Hydrocarbons	1,209.4872
Energy, from hydrogen	0.0477	CH_4	15,060.49
Energy, recovered	-1.1547	H_2	90.3379
Energy, from wind	0.0024	HCl	346.9937
Energy, unspecified	-5.1672	HF	12.9528
Resources	**mg**	NMVOC	61.4404
Water, process, drinking	16,495,064	VOC	0.8034
Water, cooling, drinking	7,205,585		
Water, process, ocean	1.831	***Emission to Water***	**mg**
Water, cooling, ocean	461.049	Phosphate	0.2682
Water, process, surface	1,062	COD	843,393.78
Water, cooling, surface	12.149	BOD	419,262.31
Water, process, well	48.240	Cl^-	1,260.933
Water,cooling,unspecified	3,220,774	Acid	0.6349

		Ammonium compounds	0.7037
		Calcium compounds	0.0046
		Calcium ion	142.6502
		CO_3^-	0.2630
		Detergent, oil	0.0658
		TOC	17.8318
		Sodium, ion	652.3222
		SO_4^-	8.041.2559
		Suspended solids	3.046.3434
		Solid Waste	**mg**
		Calcium	0.2646
		Carbon	0.1717
		Oils, unspecified	6.9754
		Sodium	0.1141

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 4.2. 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 4.2 and 4.3 show the inventory data of the sugarcane plantation and sugarcane milling in Thailand, respectively.

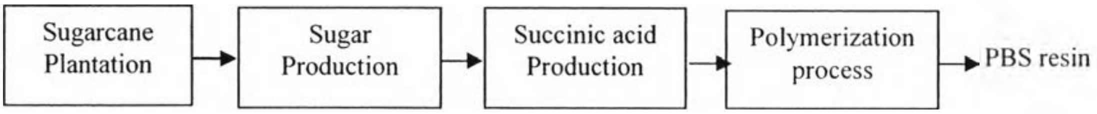


Figure 4.2 A simple process diagram of PBS resin production.

Table 4.2 Results of the inventory analysis of sugarcane plantation in Thailand

Input Inventory		
Type	**Unit**	**Amount**
Fuel		
Diesel	liter	0.222
Chemical:		
Fertilizer (N)	kg	0.277
Fertilizer (P)	kg	0.129
Fertilizer (K)	kg	0.115
Paraquat	kg	0.002
Glyphosate	kg	0.000
Atrazine	kg	0.007
Ametryne	kg	0.005
2,4-D	kg	0.002
Output Inventory		
Type	**Unit**	**Amount**
Product		
Sugarcane	kg	155.576
Co-product		
Cane trash - 0% burning	kg	31.115

Table 4.3 Results of the inventory analysis of sugarcane milling in Thailand

Input Inventory		
Type	**Unit**	**Amount**
Raw material		
Sugarcane plant	kg	155.576
Energy		
Production of Electricity & Steam Bagasse mainly & other	kg	43.308
-Electricity from bagasse	kWh	2.703
-Steam from bagasse	kg	69.953
Chemical		
Lime	kg	0.328
Sodium chloride	kg	0.122
Hydrochloric acid	kg	7.00E-05
SiO_2	kg	3.60E-04
Biocide	kg	5.70E-04
Aluminium sulfate	kg	5.80E-04
Caustic soda flake	kg	1.80E-04
Flocculants	kg	6.00E-03
Miscellaneous	kg	8.90E-04

Output Inventory		
Type	**Unit**	**Amount**
Product		
Raw sugar	kg	12.333
White sugar	kg	1.212
Pure white sugar	kg	3.502
Co-product		
Molasses	kg	5.645
Surplus bagasse and others	kg	14.305
Electricity for sale	kWh	0.697

4.1.3 Production of Plastic Products

In this study, T-shirt bag and water bottle were selected as model products for PLA and T-shirt bag and food container were selected for 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. As a consequence, the energy consumption in bioplastic processing (mainly electricity) per kg of product or per piece of product was significantly higher than usual and a large amount of scraps was generated. From this reason, it is decided that the data for the bioplastic processing stage are to be reported in 2 cases: best case and worst case. In the best case, the electricity consumption data were extracted as the average values from Plastic Processing Industry Handbook of Department of Industrial Works (DIW). In the worst case, the actual electricity consumption data for bioplastic processing from the factories in Thailand were used. The transportations of PLA resin and PLA product were also included in this part as described in the Methodology chapter.

4.1.3.1 T-shirt Bag

T-shirt bag is a bag that use in supermarket and is produced by using blown film extrusion process. Table 4.4 indicates specifications of T-shirt bag.

Table 4.4 Specifications of T-shirt bag from Company A and B

Bioplastic Product	Size	Weight (per piece)
T-shirt bag A	255mm.x310mm.x0.020mm.	0.0038 kg
T-shirt bag B	445mm.x1300mm.x0.016mm.	0.0051 kg

T-shirt bag data were collected from the two companies according to the process shown in Figure 4.3. Their processes are slightly different and are assumed to be the same in this study. The process consists of three main steps: blowing, printing, 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 T-shirt bag production from Company A and B based on one kg of bioplastic product are shown in Table 4.5.

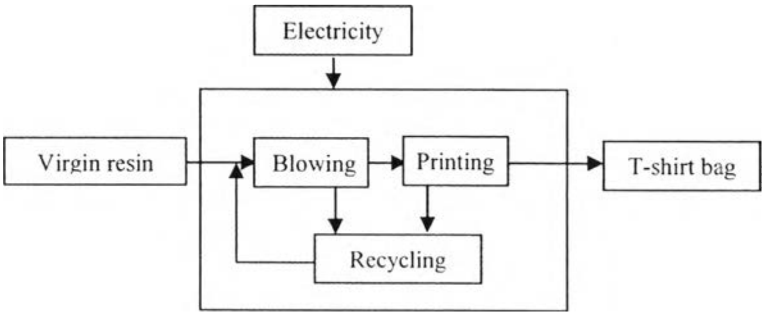


Figure 4.3 A T-shirt bag production process.

Table 4.5 Results of the inventory analysis of T-shirt bag production from Company A and B based on one kg of bioplastic product

Transportation of PLA resin							
Input Inventory				**Output Inventory**			
Descriptioin	**Unit**	**Amount**		**Description**	**Unit**	**Amount**	
Resource		A	B	***Product***		A	B
Diesel	kg	0.000999	0.001023	PLA resin	kg	1.2654	1.296
				Emission to air			
				NO_x	g	0.2073	0.2123
				CO	g	0.3597	0.3684
				CO_2	g	19.8827	20.3635
				PM	g	0.0551	0.0564
Blowing							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**		**Description**	**Unit**	**Amount**	
Resources		A	B	***Products***		A	*B*
Virgin PLA resin	g	1265.4	1296	Unprinted bag	g	1105.3	1103.4
Recycle PLA resin	g	66.6	62.7	***Solid Waste***			
Utilities				Scrap	g	226.7	255.3
Electricity*	kWh	0.9524-6.7990	1.2509-8.9302				
Printing							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**		**Description**	**Unit**	**Amount**	
Resources		A	B	***Products***		A	B
Unprinted bag	g	1105.3	1103.4	Uncut bag	g	998.7	1061.9
Printing color A	g	1.3	1.38	***Solid Waste***			
Utilities				Scrap	g	106.6	41.5
Electricity	kWh	0.323	0.34				

Recycling							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**		**Description**	**Unit**	**Amount**	
Resources		**A**	**B**	***Products***		**A**	**B**
Scrap	g	66.6	62.7	Recycle PLA resin	g	66.6	62.7
Utilities							
Electricity	kWh	0.0351	0.039				
Transportation of PLA product							
Input Inventory				**Output Inventory**			
Descriptioin	**Unit**	**Amount**		**Description**	**Unit**	**Amount**	
Resource		**A**	**B**	***Product***		**A**	**B**
Diesel	kg	0.000403	0.0004	T-shirt bag	kg	1	1
				Emission to air			
				NO_x	g	0.0836	0.0831
				CO	g	0.1451	0.1441
				CO_2	g	8.0184	7.9672
				PM	g	0.0222	0.0221

**Note: Electricity of blowing process was showed 2 cases as best case and worst case, respectively.*

At present, this product has not been produced in Thailand so the product and the process are assumed to be the same as PLA T-shirt bag as shown in Table 4.6. 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 from Company A. Table 4.7 shows the inventory data of PBS T-shirt bag.

Table 4.6 Specifications of PBS T-shirt bag from Company A

Bioplastic Product	Size	Weight (per piece)
T-shirt bag A	255mm.x310mm.x0.020mm.	0.0038 kg

Table 4.7 Results of the inventory analysis of PBS T-shirt bag production from Company A based on one kg of bioplastic product

Transportation of PBS resin					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource		**A**	***Product***		**A**
Diesel	kg	0.000999	PBS resin	kg	1.2654
			Emission to air		
			NO_x	g	0.2073
			CO	g	0.3597
			CO_2	g	19.8827
			PM	g	0.0551
Blowing					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources		**A**	***Products***		**A**
Virgin PBS resin	g	1265.4	Unprinted bag	g	1105.3
Recycle PBS resin	g	66.6	***Solid Waste***		
Utilities			Scrap	g	226.7
Electricity*	kWh	0.9524-6.7990			
Printing					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources		**A**	***Products***		**A**
Unprinted bag	g	1105.3	Uncut bag	g	998.7
Printing color A	g	1.3	***Solid Waste***		
Utilities			Scrap	g	106.6
Electricity	kWh	0.323			
Recycling					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resources		**A**	***Products***		**A**
Scrap	g	66.6	Recycle PBS resin	g	66.6
Utilities					
Electricity	kWh	0.0351			

Transportation of PBS product					
Input Inventory			**Output Inventory**		
Descriptioin	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource		**A**	***Product***		**A**
Diesel	kg	0.000403	T-shirt bag	kg	1
			Emission to air		
			NO_x	g	0.0836
			CO	g	0.1451
			CO_2	g	8.0184
			PM	g	0.0222

**Note: Electricity of blowing process was showed 2 cases as best case and worst case, respectively.*

4.1.3.2 Food Container

Food container is a box that uses for containing food and is produced by using thermoforming process. Table 4.8 gives a detail of food container.

Table 4.8 Specification of food container from Company C

Bioplastic Product	Size	Weight (per piece)
Food container	22 cm X 11cm X 4.5 cm 2 mm	149.10 g

The inventory data for the food container production were collected from Company C. The thermoforming process is divided into two main steps which are drying and thermoforming as shown in Figure 4.4. Mixed resins of PLA and PBS (35%:65%) are used in this process, which consist of PLA resin 397.39 g and PBS resin 738.01 g. Firstly, the virgin resin (mixed PBS and PLA resins) is dried by a drying machine. The resin is then formed into food container. Results of the inventory analysis of food container production based on one kg of bioplastic product are shown in Table 4.9.

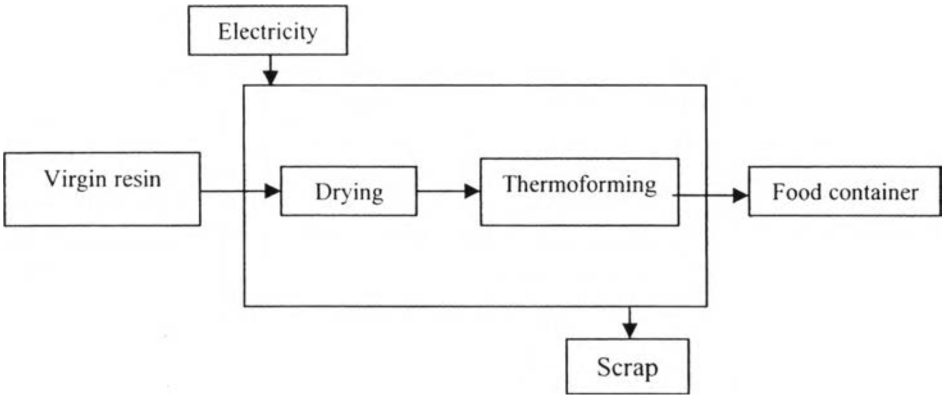


Figure 4.4 Food container production process.

Table 4.9 Results of the inventory analysis of food container production from Company C based on one kg of bioplastic product

Transportation of PLA and PBS resin							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Resources				***Products***			
Diesel	kg	0.000897		PLA&PBS resin	kg	1.1354	
				Emission to air			
				NO_X	g	0.1859	
				CO	g	0.3227	
				CO_2	g	17.84	
				PM	g	0.0494	
Drying							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Resources				***Products***			
Virgin PBS resin	g	738.01		Dried resin	g	1135.4	
Virgin PLA resin	g	397.39					
Utilities							
Electricity	kWh	1.75					

Thermoforming							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Resources				***Products***			
Dried resin	g	1135.4		Food container	kg	1	
Utilities				***Solid Waste***			
Electricity*	kWh	0.69-2.38		Scrap	g	135.4	
Transportation of product							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Resources				***Products***			
Diesel	kg	0.000594		Food container	kg	1	
				Emission to air			
				NO_x	g	0.1231	
				CO	g	0.2137	
				CO_2	g	11.8116	
				PM	g	0.0327	

**Note: Electricity of thermoforming process was showed 2 cases as best case and worst case, respectively.*

4.1.3.3 Water Bottle

Water bottle is a bottle that uses for containing water and is produced by using Injection stretch blow molding (ISBM) process. The specification of water bottle is shown in Table 4.10.

Table 4.10 Specification of water bottle from Company D

Bioplastic Product	Size	Weight (per piece)
Water bottle	Height: 14.5 cm, r: 2.5 cm, Size: 250 ml.	18.68 g (excluding water) 268.68 g (including water)

The PLA-based water bottle production data were collected from Company D. Figure 4.5 illustrates the water bottle production process. First, the preform (also known as parison) is produced by using an injection molding machine. The preform is then transferred to a blow molding machine where it is stretched in the axial direction and blown in the hoop direction to achieve biaxial orientation of the polymer, resulting in the PLA bottle. Second, cap is produced by using injection process. Table 4.11 shows the results of the inventory analysis of water bottle production based on one kg of bioplastic product. For water bottle, not only electricity consumption was different between the best case and worst case, but the amount of plastic resin used to produce the bottle was also different as shown as a range in table.

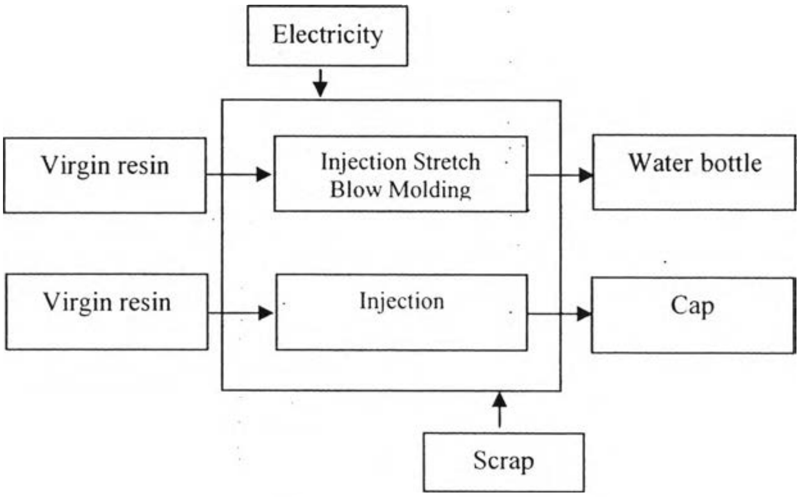


Figure 4.5 Water bottle production process.

Table 4.11 Results of the inventory analysis of water bottle production from Company D based on one kg of bioplastic product

Transport PLA resin							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Resources				***Products***			
Diesel*	kg	0.00081- 0.00111		PLA resin*	g	1026.3-1399.5	
				Emission to air			
				NO_X*	g	0.1681-0.2293	
				CO*	g	0.2917-0.3978	
				CO_2*	g	16.1258-21.9897	
				PM*	g	0.0447-0.0609	

Injection Stretch Blow Molding

Input Inventory				Output Inventory			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Resources				***Products***			
Virgin PLA resin*	g	1026.3-1399.5		PLA bottle	g	933	
Utilities				***Solid Waste***			
Electricity*	kWh	2.596-3.541		Scrap*	g	93.3-466.5	

Injection

Input Inventory				Output Inventory			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Resources				***Products***			
Virgin PLA resin*	g	73.7-100.5		Cap	g	67	
Utilities				***Solid Waste***			
Electricity*	kWh	0.15-0.205		Scrap*	g	6.7-33.5	

Transport PLA product

Input Inventory				Output Inventory			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Resources				***Products***			
Diesel	kg	0.000488		PLA bottle	g	1000	
				Emission to air			
				NO_X	g	0.1012	
				CO	g	0.1755	
				CO_2	g	9.7022	
				PM	g	0.0269	

**Note: These data show 2 cases as best case and worst case, respectively.*

4.1.4 Disposal Phase

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 ulilities, 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.

4.1.4.1 PLA Product

4.1.4.1.1 Landfill

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. In case of landfill with energy recovery, 45% of methane generated was recovered and combusted to generate electricity and the other 55% escaped to the atmosphere. The results of the inventory analysis of landfill scenario based on one kg of bioplastic waste are shown in Table 4.12 – 4.13.

Table 4.12 Results of the inventory analysis of landfill scenario (without energy recovery) based on one kg of PLA bioplastic waste

Landfill scenario (without energy recovery)							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Bioplastic waste collection							
Resources				***Emission to Air***			
Diesel	l	10.61		CO	g	315	
				CO_2	g	26,950	
				CH_4	g	2.1	
				NO_x	g	350	
				N_2O	g	1.05	
				NMVOC	g	66.5	
Landfill							
Resources				***Emission to Air***			
Bioplastic waste	kg	1		CO	g	0.09	
Diesel	kg	0.00513		CO_2 (fossil)	g	16.34	
Electricity	kWh	0.00225		CH_4	g	0.02	
Tap water	kg	0.00493		NO_x	g	0.32	
Wire	kg	0.00164		N_2O	g	0.0004	
				SO_x	g	0.02	
				CO_2 (biogenic)	g	1626.35	
				Emission to Water			
				BOD	g	0.0658	
				COD	g	0.1088	

Table 4.13 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**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Bioplastic waste collection							
Resources				***Emission to Air***			
Diesel	l	10.61		CO	g	315	
				CO_2	g	26,950	
				CH_4	g	2.1	
				NO_x	g	350	
				N_2O	g	1.05	
				NMVOC	g	66.5	
Landfill							
Resources				***Product***			
Bioplastic waste	kg	1		Electricity	kWh	1.5	
Diesel	kg	0.00513		***Emission to Air***			
Electricity	kWh	0.0164		CO	g	0.09	
Tap water	kg	0.00493		CO_2 (fossil)	g	16.34	
Wire	kg	0.00164		CH_4	g	0.02	
				NO_x	g	0.32	
				N_2O	g	0.0004	
				SO_x	g	0.02	
				CO_2 (biogenic)	g	-54.82	
				Emission to Water			
				BOD	g	0.0658	
				COD	g	0.1088	

4.1.4.1.2 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 4.14 shows the results of the inventory analysis of recycling scenario based on one kg of bioplastic waste.

Table 4.14 Results of the inventory analysis of recycling scenario based on one kg of PLA bioplastic waste

Recycling scenario							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Bioplastic waste collection							
Resources				***Emission to Air***			
Diesel	l	10.61		CO	g	315	
				CO_2	g	26,950	
				CH_4	g	2.1	
				NO_x	g	350	
				N_2O	g	1.05	
				NMVOC	g	66.5	
Recycle process							
Resources				***Products***			
Bioplastic waste	kg	1		PLA resin	kg	0.81	
Water	m^3	0.005		***Emission to Air***			
Utilities				CO_2	kg	0.325	
Electricity	MJ	2.1		***Solid Waste***			
				Plastic waste	kg	0.19	

4.1.4.1.3 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 4.15 shows the results of the inventory analysis of composting scenario based on one kg of bioplastic product.

Table 4.15 Results of the inventory analysis of composting scenario based on one kg of bioplastic (PLA) product

Composting scenario							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Bioplastic waste collection							
Resources				***Emission to Air***			
Diesel	l	10.61		CO	g	315	
				CO_2	g	26,950	
				CH_4	g	2.1	
				NO_x	g	350	
				N_2O	g	1.05	
				NMVOC	g	66.5	
Composting							
Resources				***Product***			
Bioplastic waste	kg	1		Soil container	kg	0.13	
Electricity	kWh	0.0006		***Emission to Air***			
Water	l	0.0082		CO_2 (biotic)	kg	1.41	
Diesel	l	0.00003		CO_2 (abiotic)	kg	0.09040	
Electricity	kWh	0.0006		N_2O (biotic)	kg	0.00030	
				CH_4	kg	0.00030	
				NO_x	kg	0.00002	
				SO_x	kg	0.00009	
				CO	kg	0.00029	

4.1.4.1.4 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 4.16 shows the results of the inventory analysis of incineration scenario based on one kg of bioplastic product.

Table 4.16 Results of the inventory analysis of incineration scenario based on one kg of bioplastic (PLA) product

Incineration scenario							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Resources				***Products***			
Bioplastic product	kg	1		Electricity	kWh	1.5	
HCl 35%	l	0.00004					
NaOH 50%	l	0.00004		***Emission to Air***			
Lime	kg	0.00466		CO_2 (biotic)	kg	1.80	
Electricity	kWh	0.0429		CH_4 (biotic)	kg	0.0002	
Diesel	l	0.00022		N_20 (biotic)	kg	0.00006	
				CO_2 (abiotic)	kg	0.657	
				NO_x	kg	0.0008	
				CO	kg	0.00025	
				SO_x	kg	0.00002	
				CH_4	kg	0.00198	
				Emissionto Soil			
				Ash	kg	0.01	
				Emission to Water			
				Wastewater	l	0.00025	

4.1.4.2 PBS Product

4.1.4.2.1 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 4.17 – 4.18.

Table 4.17 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**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Bioplastic waste collection							
Resources				***Emission to Air***			
Diesel	l	10.61		CO	g	315	
				CO_2	g	26,950	
				CH_4	g	2.1	
				NO_x	g	350	
				N_2O	g	1.05	
				NMVOC	g	66.5	
Landfill							
Resources				***Emission to Air***			
Bioplastic waste	kg	1		CO	g	0.09	
Diesel	kg	0.00513		CO_2 (fossil)	g	926.56	
Electricity	kWh	0.00225		CH_4	g	0.02	
Tap water	kg	0.00493		NO_x	g	0.32	
Wire	kg	0.00164		N_2O	g	0.0004	
				SO_x	g	0.02	
				CO_2 (biogenic)	g	1027.66	
				***Emission to* Water**			
				BOD	g	0.0658	
				COD	g	0.1088	

Table 4.18 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**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Bioplastic waste collection							
Resources				***Emission to Air***			
Diesel	l	10.61		CO	g	315	
				CO_2	g	26,950	
				CH_4	g	2.1	
				NO_x	g	350	
				N_2O	g	1.05	
				NMVOC	g	66.5	
Landfill							
Resources				***Product***			
Bioplastic waste	kg	1		Electricity	kWh	1.5	
Diesel	kg	0.00513		***Emission to Air***			
Electricity	kWh	0.0164		CO	g	0.09	
Tap water	kg	0.00493		CO_2 (fossil)	g	86.31	
Wire	kg	0.00164		CH_4	g	0.02	
				NO_x	g	0.32	
				N_2O	g	0.0004	
				SO_x	g	0.02	
				CO_2 (biogenic)	g	78.99	
				Emission to Water			
				BOD	g	0.0658	
				COD	g	0.1088	

4.1.4.2.2 Recycling

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

4.1.4.2.3 Composting

Table 4.19 shows the results of the inventory analysis of composting technology based on one kg of bioplastic (PBS) product.

Table 4.19 Results of the inventory analysis of composting technology based on one kg of PBS product

Composting scenario							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Bioplastic waste collection							
Resources				***Emission to Air***			
Diesel	l	10.61		CO	g	315	
				CO_2	g	26,950	
				CH_4	g	2.1	
				NO_x	g	350	
				N_2O	g	1.05	
				NMVOC	g	66.5	
Composting							
Resources				***Product***			
Bioplastic waste	kg	1		Soil container	kg	0.13	
Electricity	kWh	0.0006		***Emission to Air***			
Water	l	0.0082		CO_2 (biotic)	kg	0.943	
Diesel	l	0.00003		CO_2 (abiotic)	kg	0.835	
Electricity	kWh	0.0006		CH_4	kg	0.0003	
				NO_x	kg	0.00002	
				SO_x	kg	0.00009	
				CO	kg	0.00029	

4.1.4.2.4 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 4.20 shows the results of the inventory analysis of incineration scenario based on one kg of bioplastic (PBS) product.

Table 4.20 Results of the inventory analysis of incineration scenario based on one kg of PBS product

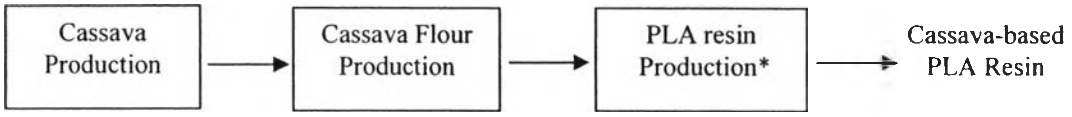
Incineration scenario							
Input Inventory				**Output Inventory**			
Description	**Unit**	**Amount**	**Remark**	**Description**	**Unit**	**Amount**	**Remark**
Resources				***Products***			
Bioplastic product	kg	1		Electricity	kWh	1.5	
HCl 35%	l	0.00004					
NaOH 50%	l	0.00004		***Emission to Air***			
Lime	kg	0.00466		CO_2 (biotic)	kg	1.08	
Electricity	kWh	0.0429		CO_2 (abiotic)	kg	0.96	
Diesel	l	0.00022		NO_x	kg	0.0008	
				CO	kg	0.00025	
				SO_x	kg	0.00002	
				CH_4	kg	0.00198	
				Emission to Soil			
				Ash	kg	0.01	
				Emission to Water			
				Wastewater	l	0.00025	

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 4.6 illustrates a simple process diagram of Cassava-based PLA resin production, which can be divided into 3 main unit processes: cassava roots production, cassava flour process, and PLA resin production. The PLA resin production is based on Ingeo production of NatureWorks (2009) which includes dextrose production, lactic acid production, and polymerization process. Figure 4.7 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 three unit process of the overall PLA resin production.



* *This process based on Ingeo production from NatureWorks 2009.*

Figure 4.6 A simple process diagram of Cassava-based PLA resin production.

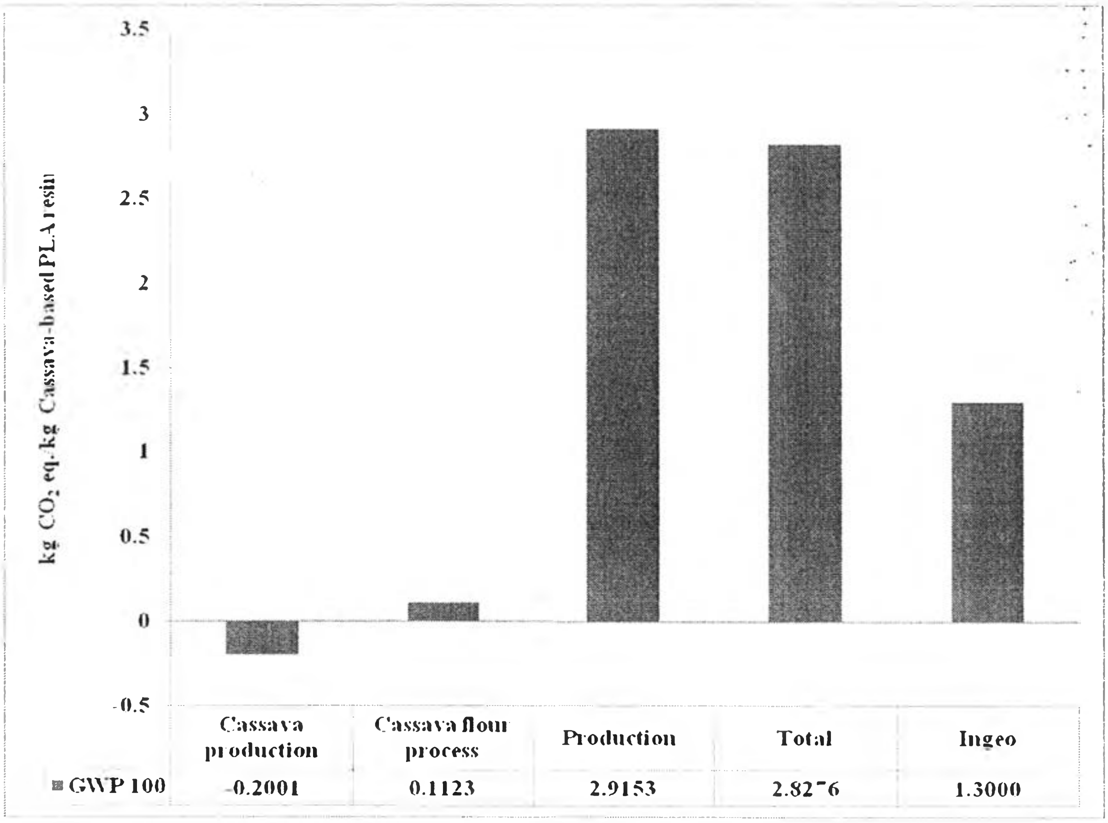


Figure 4.7 GHG emission of Cassava-based PLA resin production for each unit process by using CML 2 baseline 2000.

- Global warming potential (GWP)

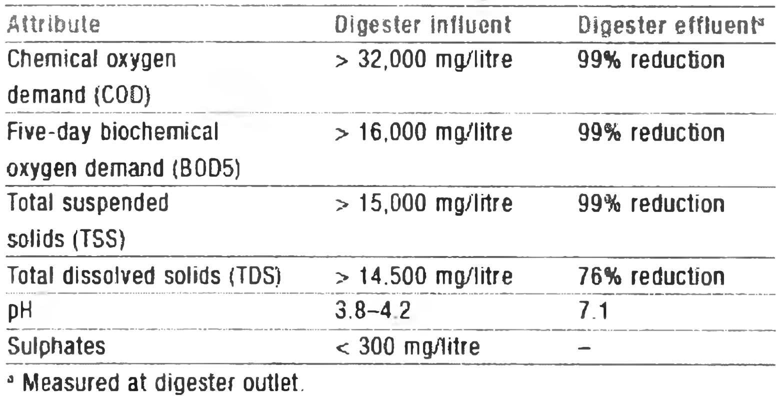
GWP impact is represented by GHG emission as shown in Figure 4.7. From the figure, it can be seen that the net GHG emission for Cassava-based PLA resin production is 2.8276 kg CO_2 eq./kg resin. The resin production phase or polylactide production has shown to have the highest contribution to GWP. This is due to the use of energy which is still based on fossil sources such as coal and natural gas. This is similar to the results recently reported by NatureWorks (Vink *et al.*, 2009) that shows the major contribution from the use of coal as energy source which leads to higher greenhouse gases emission than in their previous paper that uses renewable energy sources (Vink *et al.*, 2007). Another reason that causes high GWP value is CO_2 uptake of the crop. It is noticed that the data reported by NatureWorks (both 2007 and 2009) for CO_2 take-up from the atmosphere by corn during its growth is much higher than the amount uptake by cassava. This leads to a higher GWP for Cassava-based PLA resin in Thailand than PLA resin produced in USA (Ingeo) as shown in Fig.4.7.

Learning from the study of NatureWorks, similar treatment can be done in this study by creating options for possible improvements in some stages in the life cycle of the bioplastic, especially in the upstream process in order to reduce the GWP baseline. In this work, 2 options were offered which are 1) utilization of biogas from wastewater treatment from cassava production for electricity generation and 2) improvement of cassava yield from 3.5 to 5 ton/rai.

4.2.1.1.1 Option 1: Utilization of Biogas from Wastewater Treatment from Cassava Production

For this option, we used the secondary data extracted from Clean Development Mechanism (CDM) application documents of one of the largest cassava processing plants in Nakorn Ratchasima (Korat), Sanguanwong Industries (SWI). This plant cooperates with Korat Waste to Energy Co. Limited (KWTE), which owns and operates the facility as a renewable energy service company. They use Converted In-Ground Anaerobic Reactor (CIGAR) technology to turn wastewater into energy and then claim carbon credit through CDM. Table 4.21 gives details of the wastewater before and after digestion.

Table 4.21 SWI wastewater before and after digestion



Attribute	Digester influent	Digester effluent[a]
Chemical oxygen demand (COD)	> 32,000 mg/litre	99% reduction
Five-day biochemical oxygen demand (BOD5)	> 16,000 mg/litre	99% reduction
Total suspended solids (TSS)	> 15,000 mg/litre	99% reduction
Total dissolved solids (TDS)	> 14.500 mg/litre	76% reduction
pH	3.8–4.2	7.1
Sulphates	< 300 mg/litre	–

[a] Measured at digester outlet.

For CIGAR process (Figure 4.8), the greater conversion efficiency and higher organic load together was expected to increase about 20% more biogas produced. In addition, the greater combustion efficiency means less biogas is required to produce electricity. Combining these factors could provide up to 25% – 30% more biogas than the conventional technology. Since the commencement of CIGAR operations in 2003, the system has averaged a production of 60,000 m^3 biogas per day at 62% methane gas (equivalent to 32,000 liters of HFO per day) and the power plant has an averaged electricity generation of slightly more than 71,000 kWh per day at peak operation. Maximum biogas production at SWI's maximum wastewater flow rate of 350 m^3/hour is projected at 124,000 m^3 per day.

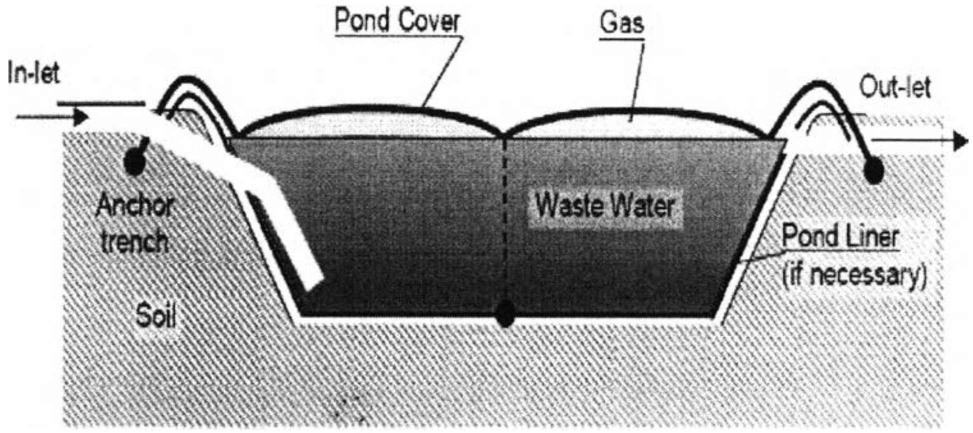


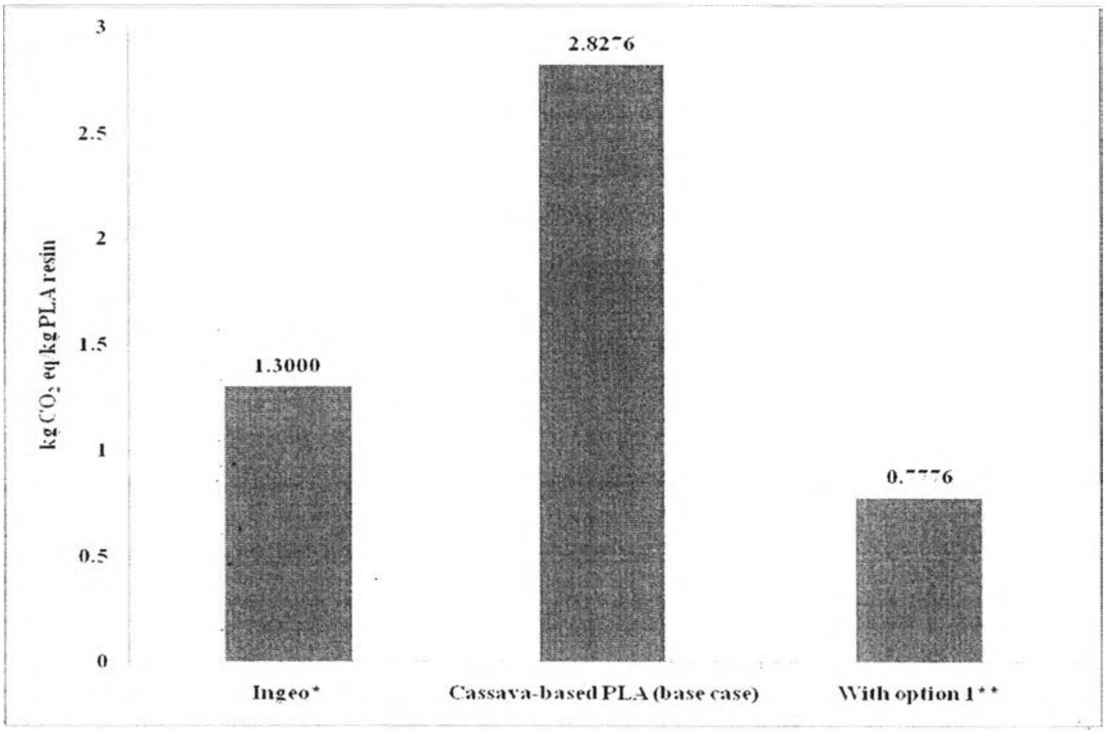
Figure 4.8 Converted in Ground Anaerobic Reactor (CIGAR).

Total system output for 2004 is projected at 24 million kWh of electricity, which will be supplied directly to the grid of EGAT. This is calculated to be equal to 380,000 tonnes of CO_2 equivalent for GHG emission reduction. Details of CIGAR performance based on tapioca starch power in Thailand are given in Table 4.22.

Table 4.22 CIGAR performance statistics (2004)

Biogas methane content	62%
Biogas production per m^3 wastewater	16.5 m^3
Methane production per m^3 wastewater	10.25 m^3
Maximum biogas production at full wastewater flow	124,000 m^3/day
GHG emission reductions	380,000 tonnes CO_2 equivalent

Figure 4.9 shows the comparison of the GWP between Ingeo and Cassava-based PLA resin (base case) and with option 1. It can be seen that GWP as shown in kg CO_2 eq./kg PLA resin decrease 4 times for Cassava-based PLA resin with option 1 when compared to the base case. Moreover, Cassava-based PLA resin production with option 1 has lower GWP than Ingeo resin of NatureWorks.



*Note: * Vink et al. 2009*

***Maximum biogas from wastewater treatment is used to produce electricity, so this process get maximum GWP reduction.*

Figure 4.9 Comparison of GWP between Cassava-based PLA resin (base case), with option 1, and Ingeo resin of NatureWorks by using CML 2 baseline 2000.

4.2.1.1.2 Option 2: Improvement of Cassava Yield from 3.5 to 5 ton/rai

This option involves the plantation phase of cassava in which the government has a plan to increase the cassava yield from the current figure of 3.5 ton/rai to 5.0 ton/rai in 2015. This is expected to be achieved through the improved cassava seeds selection for plantation. In this study, two assumptions were made that: 1) improved cassava seeds that can be planted in every area in Thailand, and 2) improved cassava yield of 5 ton/rai can be achieved by using the same amount of fertilizers and herbicides as they were used to get the yield of 3.5 ton/rai.

Based on this improvement option, the GWP could be recalculated for Cassava-based PLA resin production with option 2 as shown in Figure 4.10. It can be seen that the GHG value was reduced only about 10% compared to the base case. The effect of this option is not significant as it only helps reduce the environmental load of the cassava roots in the plantation phase whereas the other processes in the life cycle of bioplastic remain the same. This is why the 40% increase in the yield could improve only 10% of the GWP reduction.

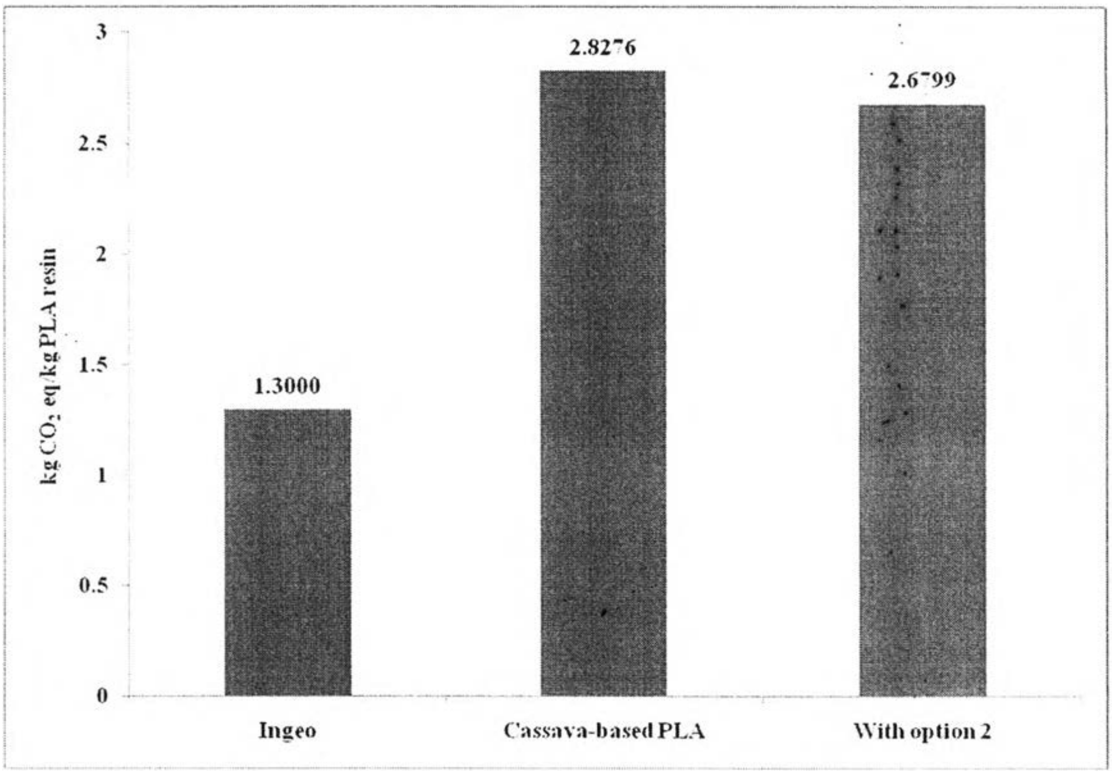


Figure 4.10 Comparison of GWP between Cassava-based PLA resin (base case), Cassava-based PLA resin with option 2, and Ingeo resin from NatureWorks by using CML 2 baseline 2000.

4.2.1.1.3 All Options

In this part, we have combined both two options together to help reduce GWP throughout the life cycle of the bioplastic. Figure 4.11 shows the GWP impact as represented by GHG emission in kg CO_2/ kg PLA resin for the base case Cassava-based PLA resin, with option 1, with option 2, and with both options compared to Ingeo resin of NatureWorks. The results shows that the GHG emission could be lowered to as low as 0.6299 kg CO_2 eq./kg PLA resin or 4.5 and 2 times lower than the base case of Cassava-based PLA resin and Ingeo resin, respectively.

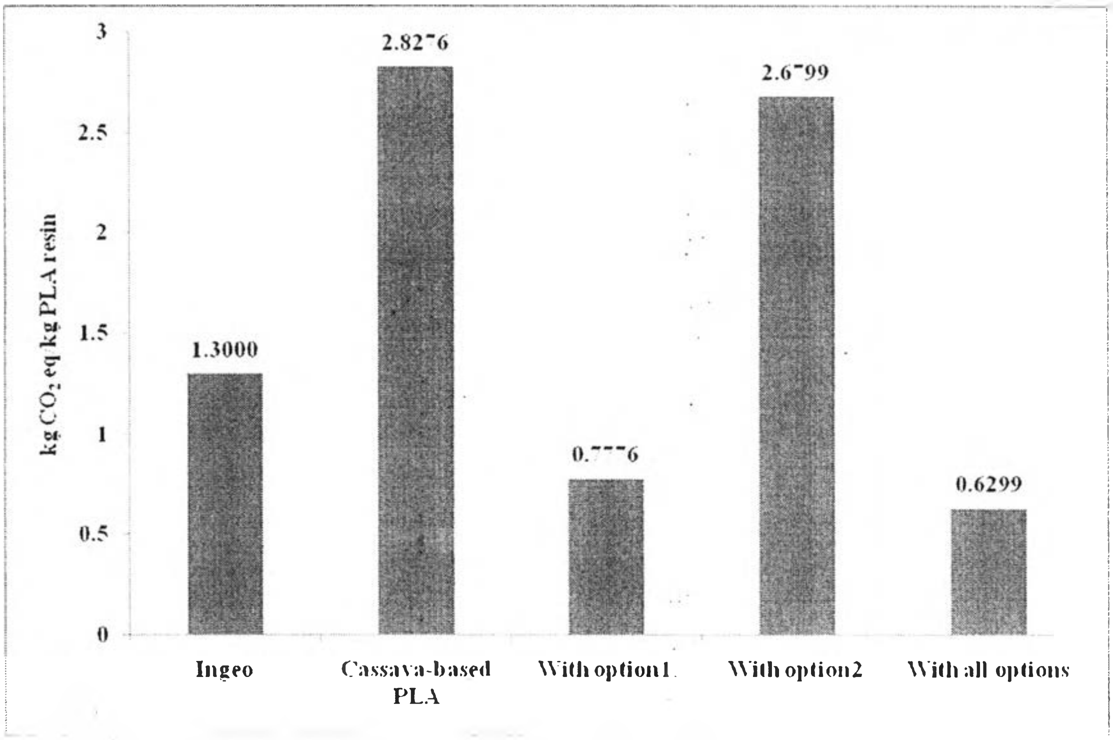


Figure 4.11 GWP of Cassava-based PLA resin for the base case, with option 1, with option 2, and with all options compared to Ingeo by using CML 2 baseline 2000.

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. However, for simplicity sake, only GWP impact from CML method (as represented by kg CO_2 eq.) is presented in this part while full results of both methods are included in the Appendix B. Figure 4.12 shows the unit processes involved in the life cycle of PBS resin production. It can be seen that the resources for PBS 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 LCIA results of GWP of PBS resin in various stages throughout its life cycle.

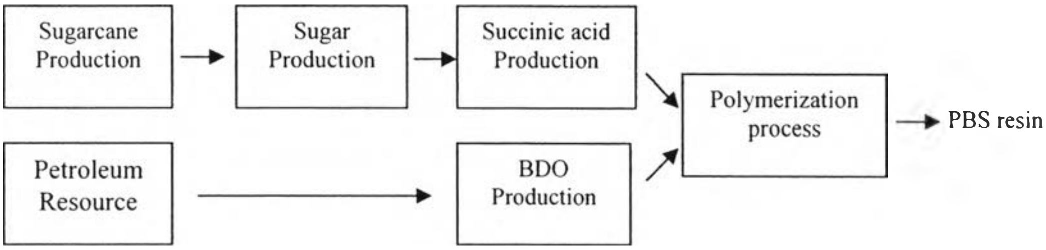


Figure 4.12 A simple process flow diagram of PBS resin production.

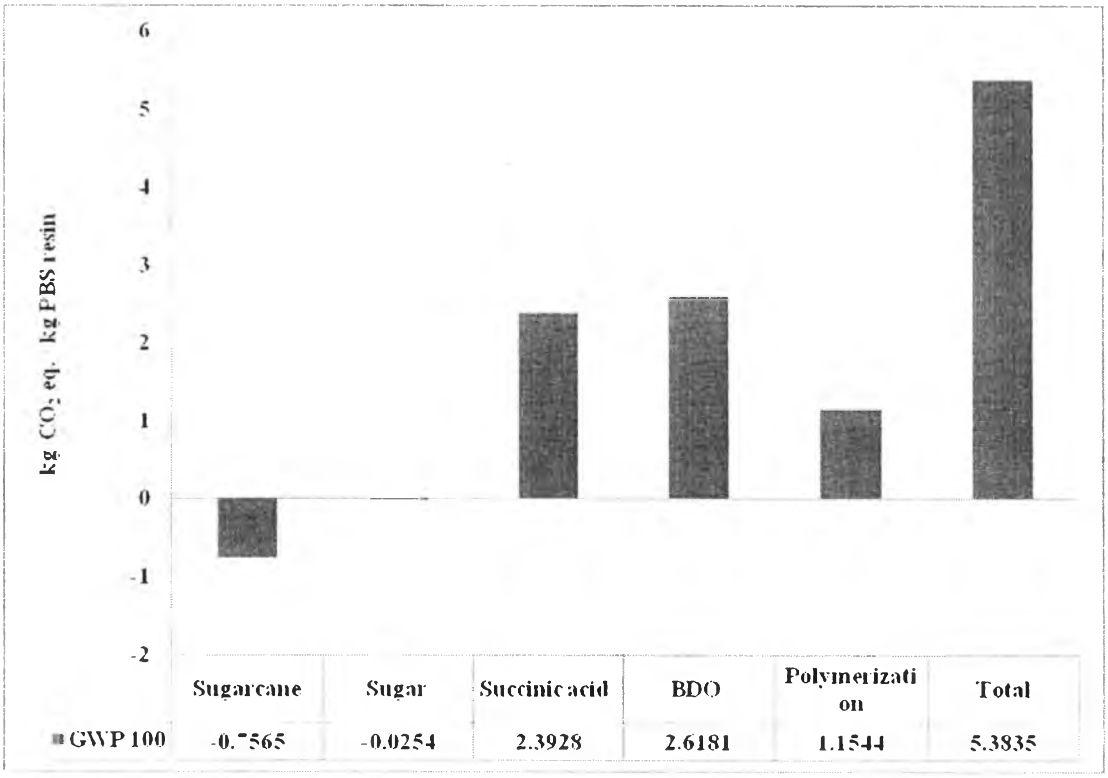


Figure 4.13 GWP of PBS resin in various life cycle stages by using CML 2 baseline 2000.

From Fig.4.13, it can be seen that succinic and BDO production contribute significantly to the GWP of PBS resin followed by polymerization process. The total GWP of PBS resin production is shown to be

5.3834 kg CO_2 eq. of which the highest amount of about 50% comes from BDO (2.6181 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.4.13 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 bagasses 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 Ingeo resin is shown in Figure 4.14. From this figure, it can be seen that GHG emission from PBS has shown to be the highest, followed by Cassava-based PLA, and Ingeo from the U.S. However, when option 1 or both options were included, GHG impact from Cassava-based PLA resin has shown to be the lowest.

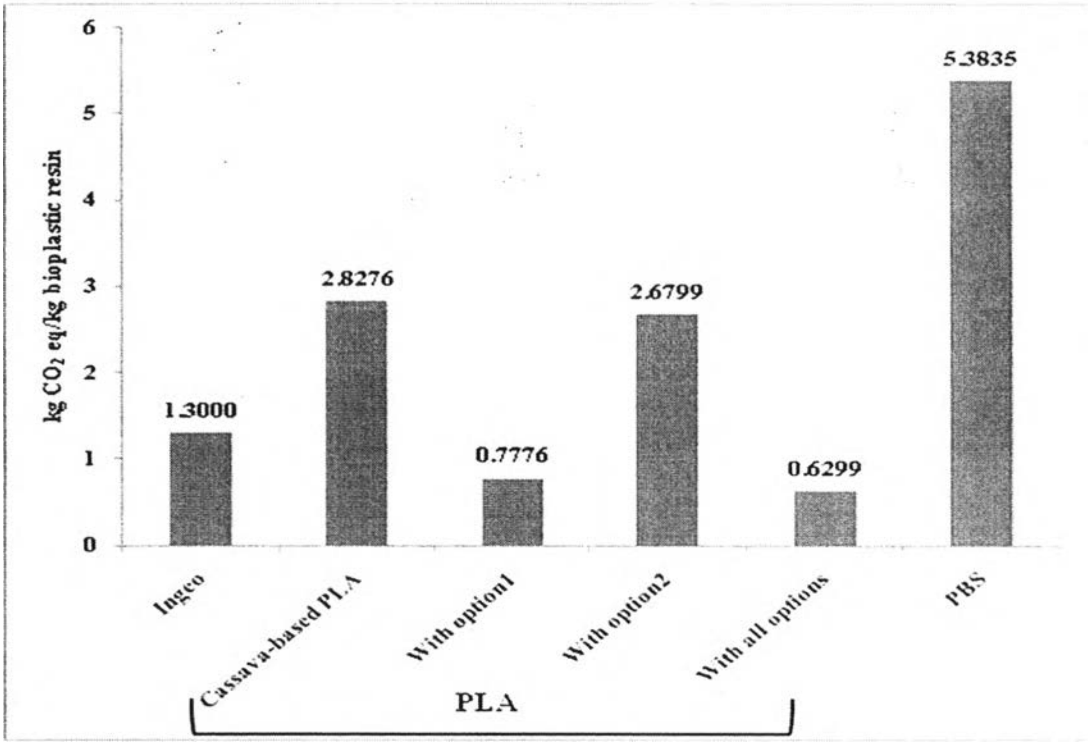


Figure 4.14 Comparison of GWP of PBS resin with Cassava-based PLA resin and Ingeo resin by using CML 2 baseline 2000.

4.2.2 Bioplastic Products

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 products. The products studied include T-shirt bag and drinking water bottle for PLA, and T-shirt bag and food container for PBS. For PLA products, cassava-based PLA resin with all options (both 1 and 2), representing the best environmental performance in the resin production phase, was used in this analysis. It should be noted that the results shown in this part were calculated from two sets of the plastic processing data: the worst case and the best case, which correspond to the data extracted from the government report for processing of conventional plastics and the actual data from the factory, respectively.

4.2.2.1 T-shirt Bag

The results presented in this part are separated into PLA T-shirt bag from Company A and Company B, and PBS T-shirt bag from Company A. In addition, for each type of bag, the results are also presented as a comparison between best case and worst case as shown in Figure 4.15. Most of the GWP impact of T-shirt bag comes from electricity use in the plastic processing. It can be seen that the GWP of the bag from Company B is slightly higher than that of Company A because it is bigger and thicker than T-shirt bag of Company A. Consequently, it requires longer processing time, leading to higher energy consumption and higher environmental burden. For PBS T-shirt bag, it has higher GWP than PLA T-shirt bags which is due to the PBS resin as shown in previous section (Fig.4.14).

4.2.2.2 Drink Water Bottle

GWP results of PLA water bottle from Company D are shown in Figure 4.16 for both best case and worst case. For water bottle, GWP value of worst case is slightly higher because the bioplastic bottles are produced not on a regular basis, but rather as a spot lot for special order. Hence, the factory is not familiar to the process conditions which results in a lot of scraps (as waste) and high electricity consumption than processing of conventional plastic.

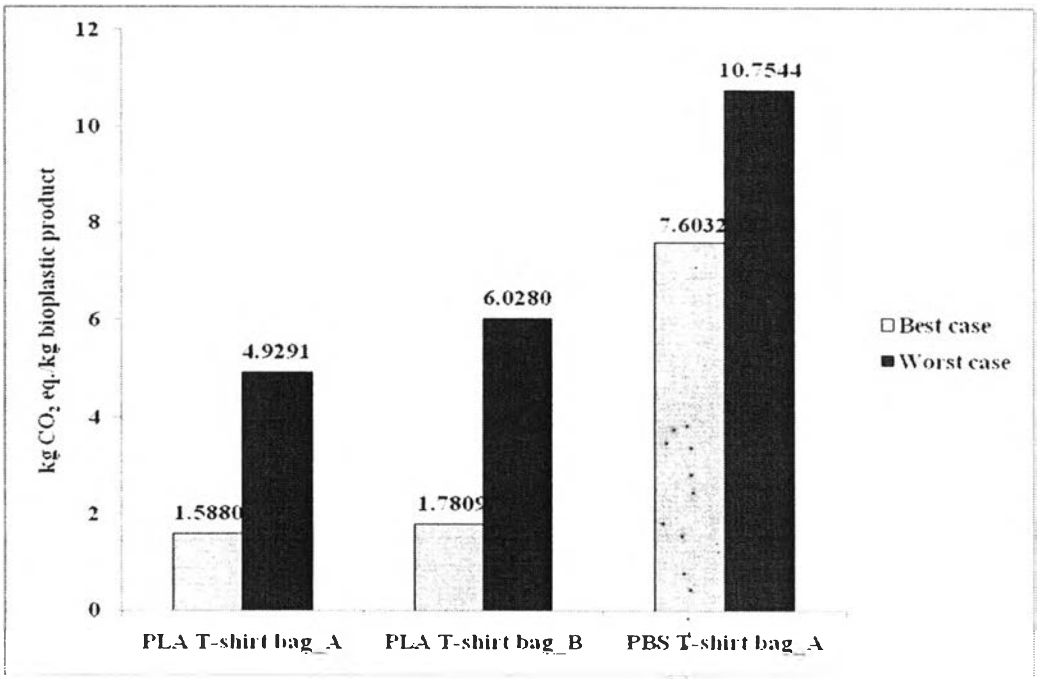


Figure 4.15 GWP of PLA and PBS T-shirt bags from Company A and B for both best case and worst case by using CML 2 baseline 2000.

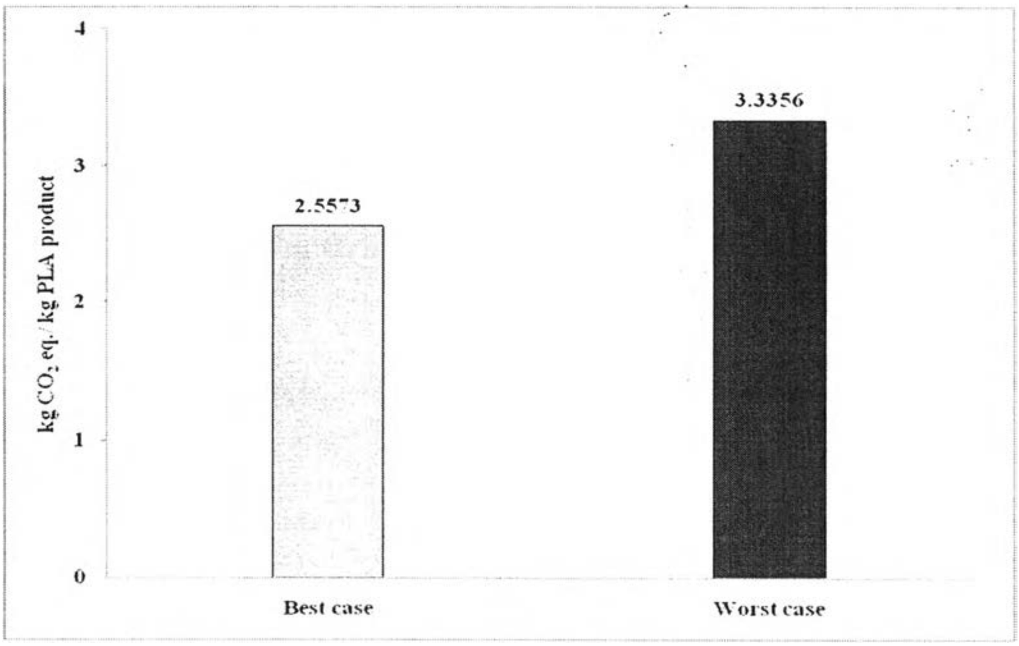


Figure 4.16 GWP of PLA water bottle from Company D for both best case and worst case by using CML 2 baseline 2000.

4.2.2.3 Food container

Figure 4.17 shows GWP of PBS food container for both best case and worst case by using CML 2 baseline 2000. Similar explanation to the drinking water bottle can be offered here for the higher impact of the worst case compared to the best case. It should be noted that in this particular case PBS was mixed with PLA (3:2) to produce food container.

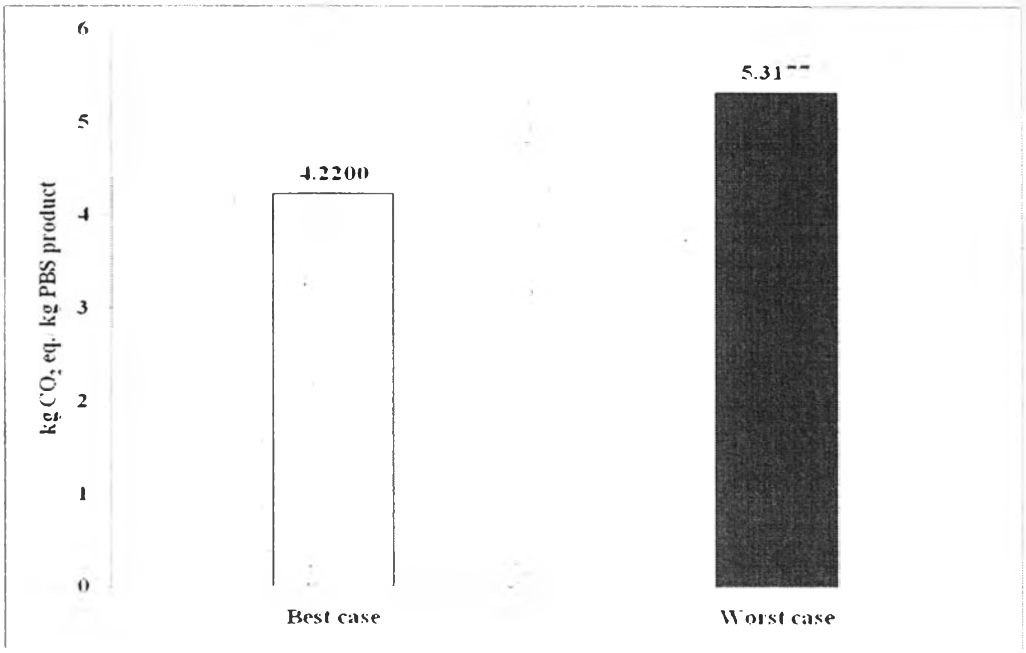


Figure 4.17 GWP of PBS food container from Company C in term of both best case and worst case by using CML 2 baseline 2000.

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); composting; incineration; and recycling, were used in this study as a means to treat bioplastic wastes. Based on these disposal technologies, four waste management scenarios (Base case, S1, S2, and S3) were created as described in the experimental section (Chapter 3) 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 products

Figure 4.18 shows GWP of the four disposal technologies based on 1 kg PLA waste being treated. Each disposal technology is discussed below.

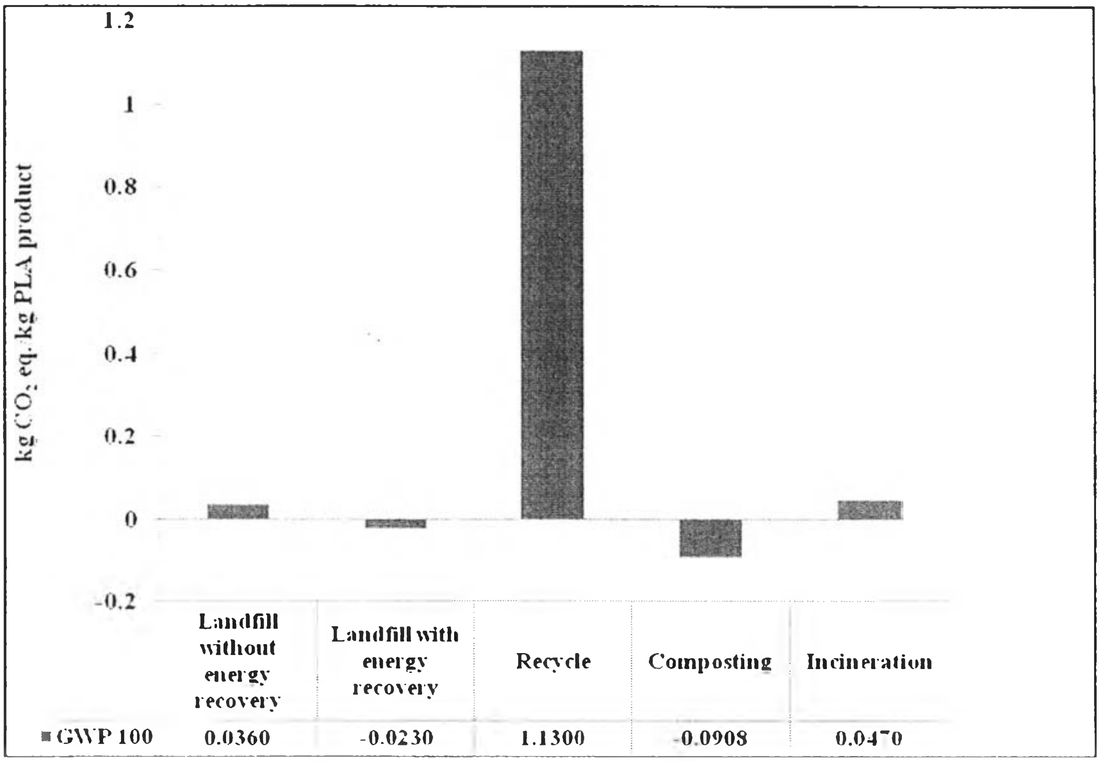


Figure 4.18 GWP of various disposal technologies based on 1 kg PLA product treated by using CML 2 base line 2000.

Landfill

From Figure 4.18, the GWP of landfill without energy recovery is 0.036 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. 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 which is 0.56 kg CO_2 eq. per kWh (grid-mixed). Thus, the total GWP for landfill with energy recovery was decreased to -0.023 kg CO_2 eq./kg PLA treated as shown in Fig.4.18.

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 new resin, this recycling activity leads to a reduction of need to produce fresh PLA resin (from virgin material) of the equal amount. Thus, the total GWP of recycling PLA waste should be deducted by the GWP of the production of fresh PLA resin (1.53 – 2.71 kg CO_2 eq. per kg PLA). As a result, the net GWP for recycling PLA waste was shown to be 1.13 kg CO_2 eq. per kg PLA treated (an average value). This is the first highest GWP among all treatment technologies which is due to complication of the process to recycle PLA back to its monomer and resin.

Composting

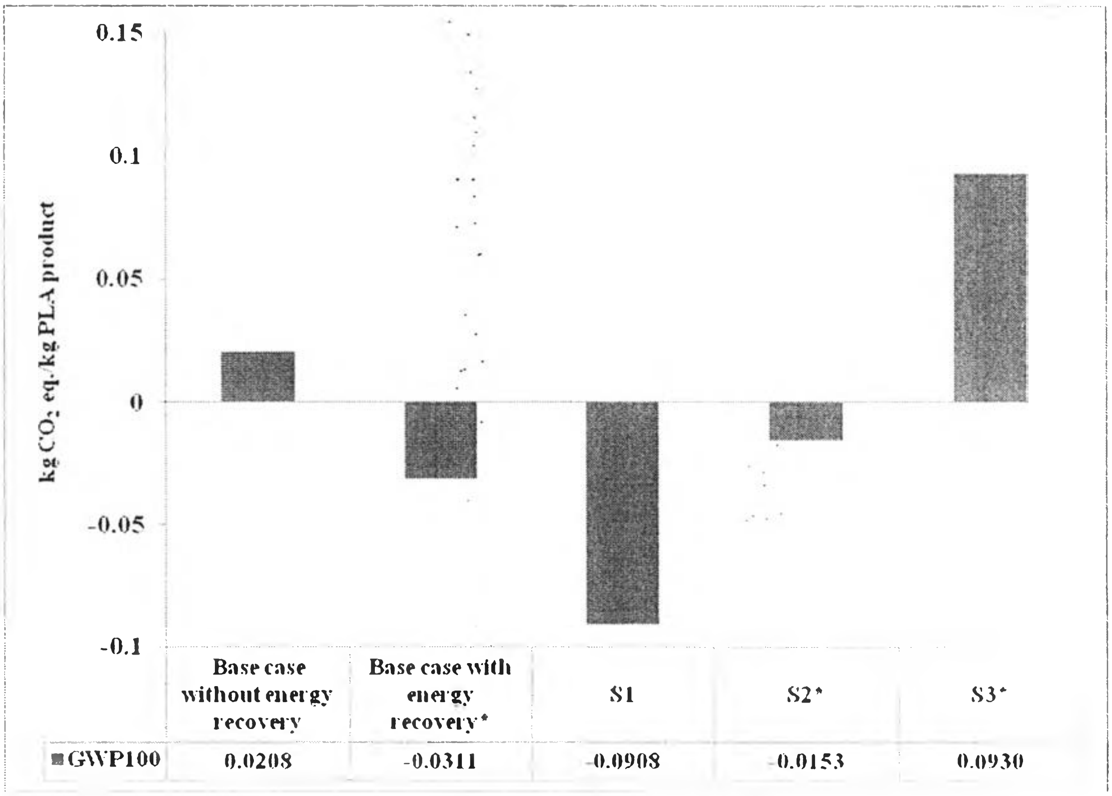
For composting, the bioplastic wastes are degraded under aerobic conditions which results in soil containing substance and emission of CO_2. As PLA is produced totally from renewable resources, the CO_2 emitted is considered carbon neutral in this study (not counted as GHG emission). The soil containing substance from the composting process is usually mixed with animal manure and utilized as soil container which can replace the use of organic compost. Thus, the total GWP of the composting process should be compensated by the GWP of organic compost production. As a result, the net GWP of composting technology is -0.0908 kg CO_2 eq./kg PLA treated. As shown in Fig.4.18, 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 0.047 kg CO_2 eq. per kg PLA treated as shown in Figure 4.18.

After all four disposal technologies were evaluated and compared in the previous section; they were integrated into four waste management scenarios (Base case, S1, S2, and S3) as described in the experimental chapter (Chapter 3). For the base case, it is considered as 2 sub-categories, depending on whether or not the energy recovery is included in the landfill. For other scenarios (S1 – S3), the landfill with energy recovery was used in the analysis. Figure 4.19 illustrates the comparison of all disposal scenarios included in this study based on 1 kg PLA product. From this figure, the results show that the base case without energy recovery, which represents the current waste management of Bangkok (12%

composting and 88% landfill) has GWP impact of approximately 0.02 kg CO_2 eq. per kg PLA product. However, when energy recovery is included, the GWP of the base case scenario was significantly reduced to -0.0311 kg CO_2 eq. Considering all waste management scenarios, the best case of disposal scenario has shown to be S1 (100% composting) which has GWP of -0.0908 kg CO_2 eq. per kg PLA product, and the worst case is S3 (30% landfill with energy recovery, 30% composting, 30% incineration, and 10% recycle) has shown GWP distribution 0.0930 kg CO_2 eq. per kg PLA product.



Note: These scenarios use landfill with energy recovery

Figure 4.19 Comparison of GWP for various waste management scenarios for PLA based on 1 kg PLA product treated by using CML 2 base line 2000.

4.2.3.2 PBS products

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. After that, the disposal technologies were integrated into four waste management scenarios (Base case, S1, S2, and S3) in order to evaluate the best scenario 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, as shown in Fig.4.13. 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 4.20 shows GWP of all three disposal technologies based on 1 kg PBS product.

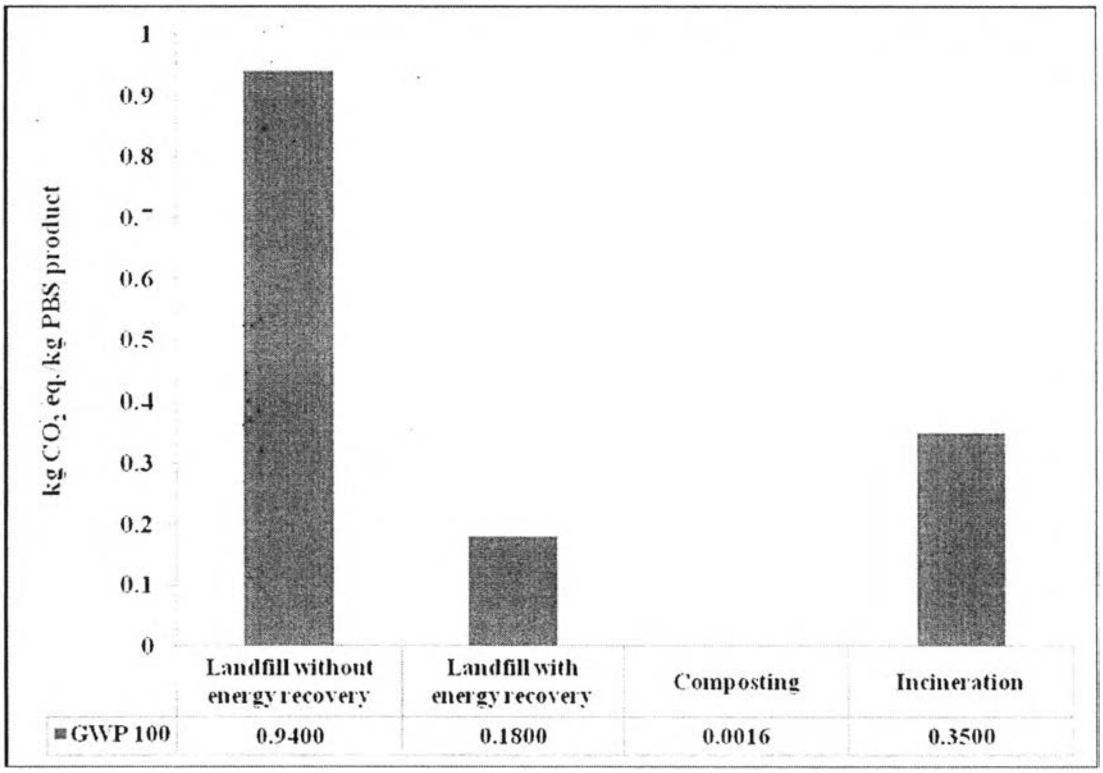


Figure 4.20 GWP of three disposal technologies based on 1 kg PBS product by using CML 2 base line 2000.

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 0.94 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) (0.56 kg CO_2/kWh). After the compensation of this electricity, the total GWP is reduced to 0.18 kg CO_2 eq./kg PBS treated. When compared to PLA (Fig.4.18), 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 soil container to help reduce the use of organic compost. After the compensation of the GWP of organic compost production, the net total GWP of the composting process for PBS wastes is 0.0016 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 (0.35 kg CO_2 eq./ kg PBS treated) when compared to PLA (Fig.4.18).

These three disposal technologies were calculated into three waste management scenarios (Base case, S1, and S2) which is one scenario (S3) fewer than in PLA case because recycle of PBS was not included in the study. The analysis was done similar to PLA such that the base case was considered as 2 sub-categories, depending on whether or not the energy recovery is included in the landfill. For other scenarios (S1 and S2), the landfill with energy recovery was used in the analysis. Figure 4.21 illustrates the comparison of all waste management scenarios included in this study for PBS based on 1 kg PBS treated. From this figure, the results show that the base case without energy recovery (representing current waste management of Bangkok which consists of 12% composting and 88% landfill without energy recovery) has shown to be the worst case for PBS disposal scheme. However, if the energy recovery is included, the GWP is reduced to 0.1586 kg CO_2 eq. which is the second best disposal scenario. It should be noted that 100% composting scenario (S1) has shown to be the first best scenario which has GWP of as low as 0.0016 kg CO_2 eq./kg PBS treated.

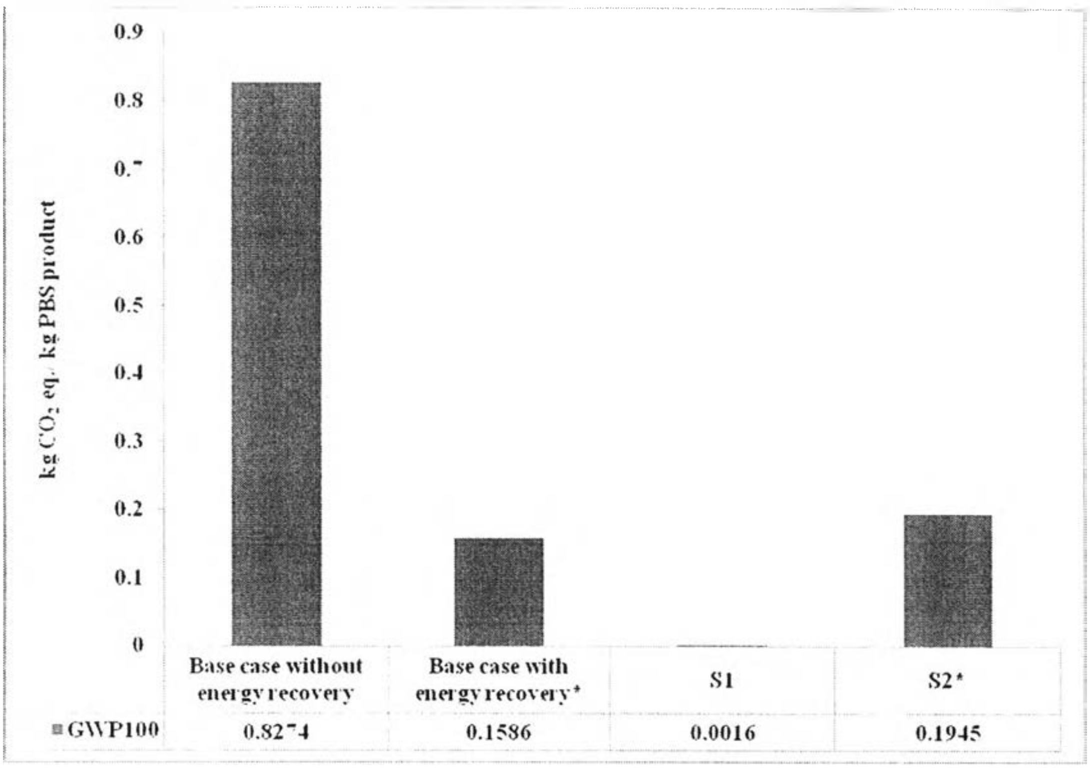


Figure 4.21 Comparison of GWP of various waste management scenarios for PBS based on 1 kg PBS treated by using CML 2 base line 2000.

4.2.4 Cradle to Grave

In this part, the environmental impact assessment of the whole life cycle of bioplastics or "cradle-to-grave" was performed which combines all phases throughout the life cycle of PLA and PBS, including four main phases as discussed in sections 4.2.1, 4.2.2, and 4.2.3: resin production, processing of bioplastic products, transportation, and disposal.

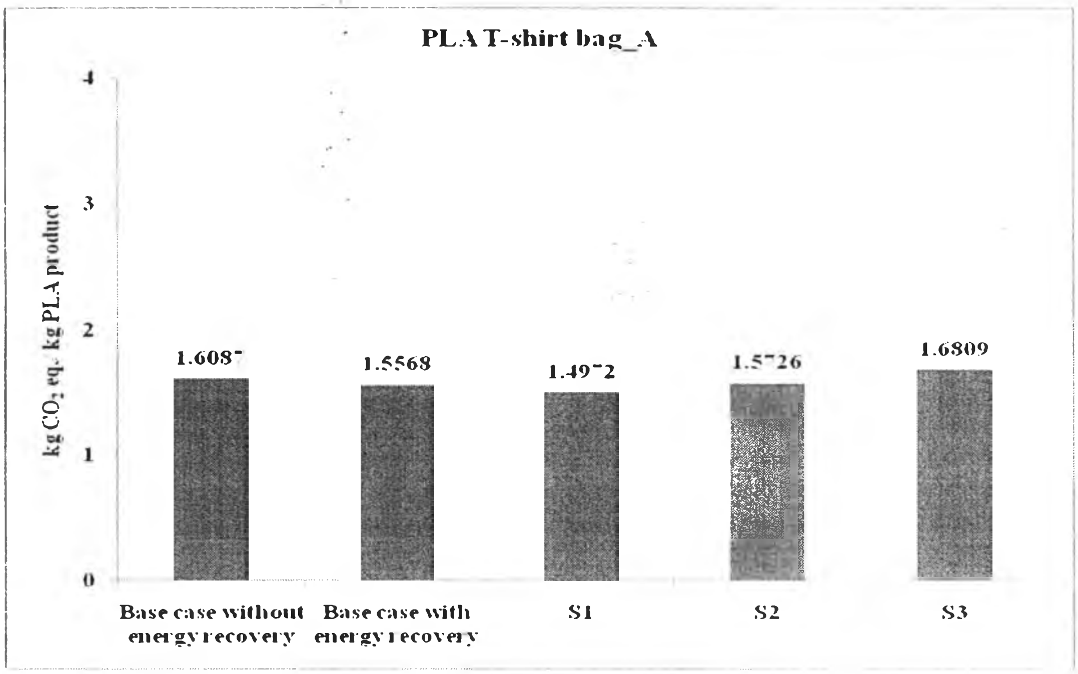
4.2.4.1 Whole Life Cycle of PLA Products

The entire life cycle of PLA product composes of PLA resin production and transportation, product processing, transportation of PLA product, and disposal phase. Two PLA products were selected as a model to study which are T-shirt bag and drinking water bottle. In this study, the environmental impact category of interest is GWP which is analyzed for each product and for all waste management scenarios per kg of PLA product.

4.2.4.1.1 PLA T-shirt Bag

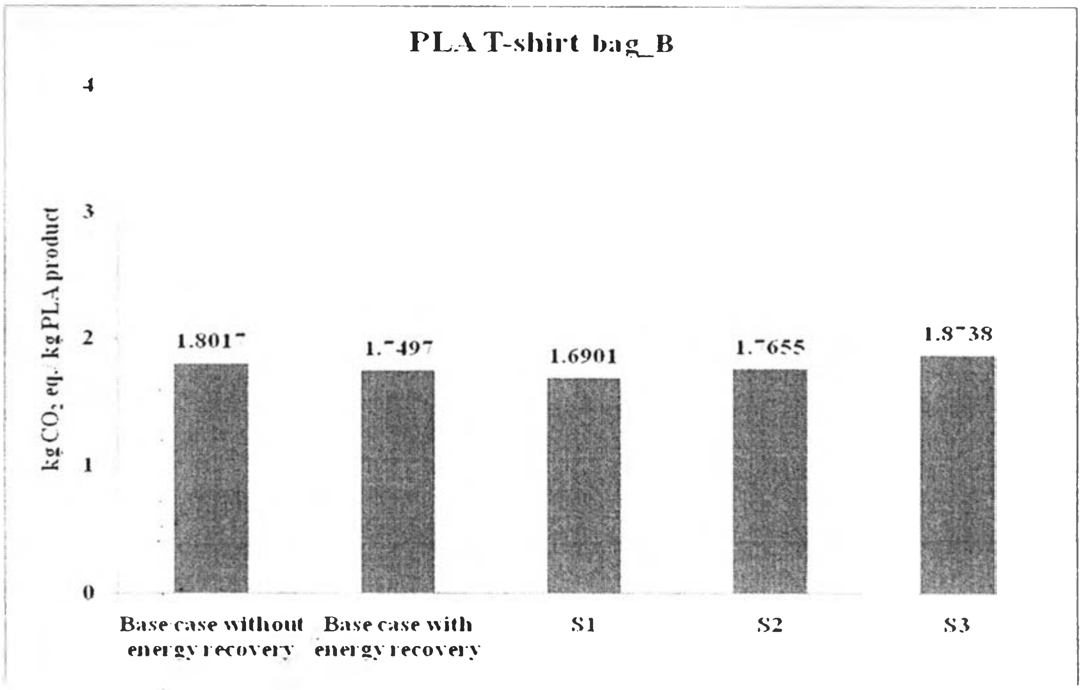
The life cycle GWP of PLA T-shirt bag A for all waste management scenarios is shown in Figure 4.22. S3 (30% landfill with energy recovery, 30% composting, 30% incineration, and 10% recycle) has shown to have the highest impact of 1.6809 kg CO_2 eq. while S1 (100% composting) has shown to be the best scenario which has lowest GWP of 1.4972 kg CO_2 eq. /kg PLA product.

As shown in Figure 4.23, the GWP of T-shirt bag B for S3 (30% landfill with energy recovery, 30% composting, 30% incineration, and 10% recycle) is shown to be 1.8738 kg CO_2 eq./kg PLA product which is the highest and slightly higher than T-shirt bag A. Similar to T-shirt bag A, S1 (100% composting) has shown to be the best scenario among all scenarios studied as it provides the lowest GWP of 1.6901 kg CO_2 eq. /kg PLA product.



**Note: For S2 and S3, landfill with energy recovery is used in these scenarios.*

Figure 4.22 Life cycle GWP of PLA T-shirt bag A by using CML 2 baseline 2000.

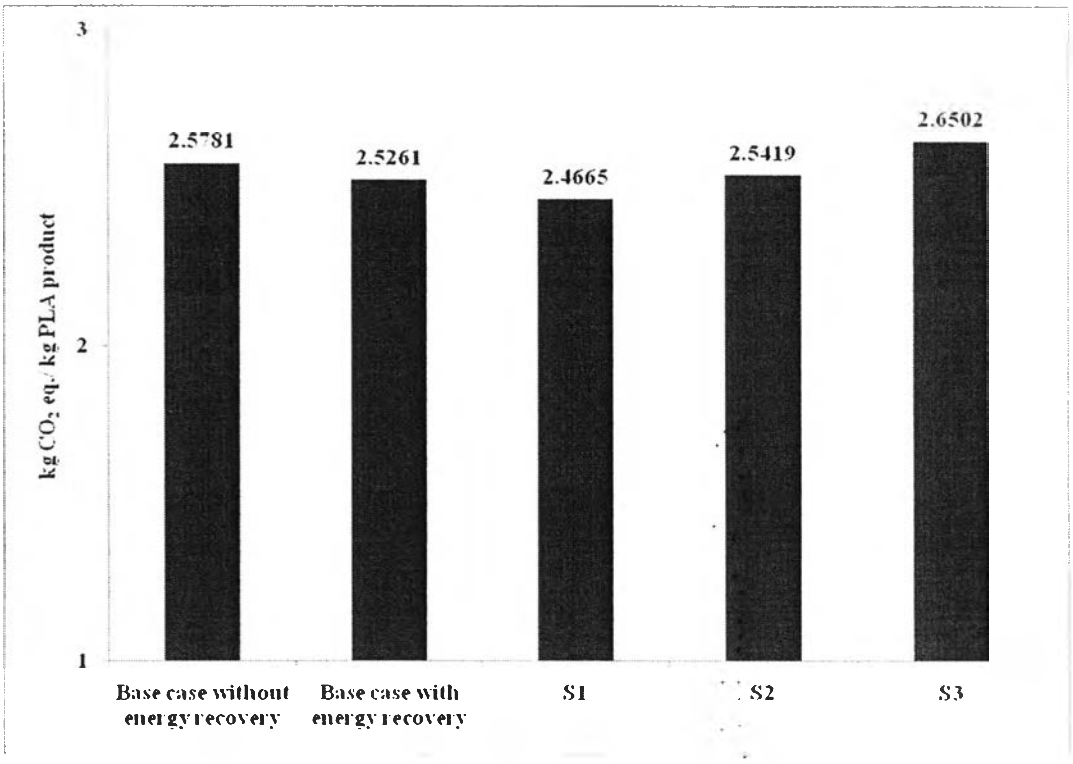


**Note: For S2 and S3, landfill with energy recovery is used in these scenarios.*

Figure 4.23 Life cycle GWP of PLA T-shirt bag B by using CML 2 baseline 2000.

4.2.4.1.2 PLA Drink Water Bottle

The life cycle GWP of PLA drinking water bottle for all waste management scenarios is shown in Figure 4.24. S3 (30% landfill with energy recovery, 30% composting, 30% incineration, and 10% recycle) has shown to have the highest impact of 2.6502 kg CO_2 eq. per kg PLA product while S1 (100% composting) has shown to be the best scenario which has lowest GWP of 2.4665 kg CO_2 eq. /kg PLA product. Comparing to the results shown in Fig.4.22 and 4.23, it can be seen that the GWP values of PLA drinking water bottle are higher than GWP of T-shirt bag on the same weight basis for all cases studied. This may be attributed to the more complicated process of drinking water bottle which consists of two parts: bottle and cap. Higher amount of plastic wastes was also reported by the manufacturer.



**Note: For S2 and S3, landfill with energy recovery is used in these scenarios.*

Figure 4.24 Life cycle GWP of PLA water bottle using CML 2 baseline 2000.

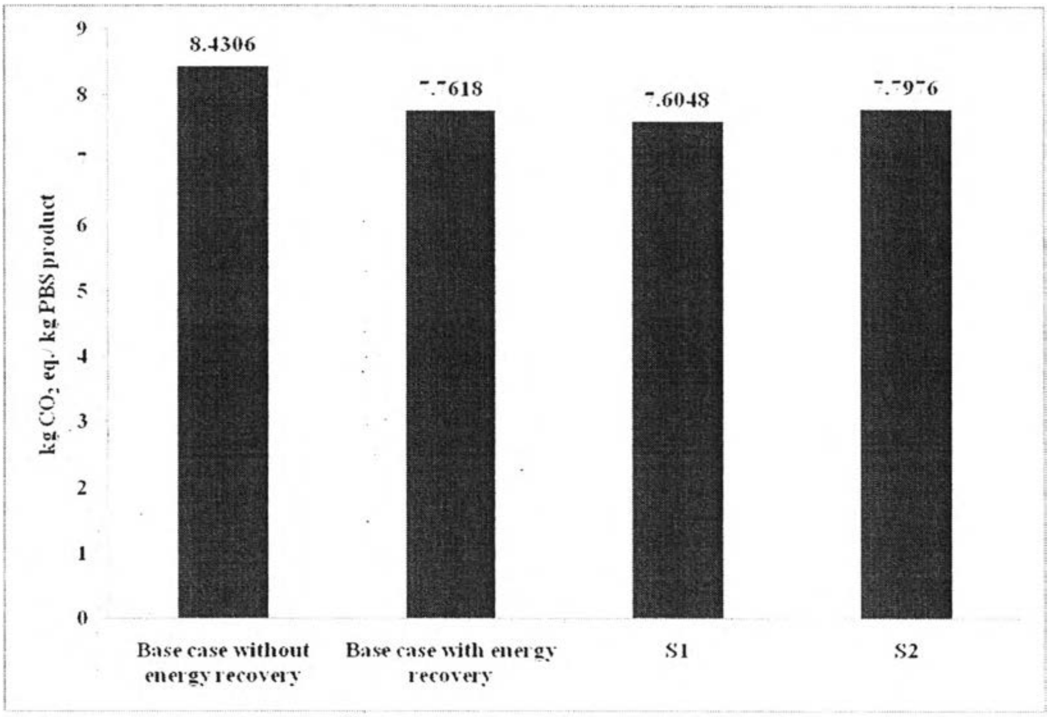
4.2.4.2 Whole Life Cycle of PBS Products

The entire life cycle of PBS product composes of PBS resin production and transportation, product processing, transportation of PBS product, and disposal phase. Two PBS products were selected as a model to study which are T-shirt bag and food container. In this study, the environmental impact category of interest is GWP which is analyzed for each product and for all waste management scenarios per kg of PBS product.

4.2.4.2.1 PBS T-shirt Bag

The life cycle GWP of PBS T-shirt bag for all waste management scenarios is shown in Figure 4.25. From this figure, we can see that the base case without energy recovery has shown to have the highest impact of 8.4306 kg CO_2 eq./ kg PBS product while S1 (100% composting) has shown to be the best scenario which has lowest GWP of 7.6048 kg CO_2 eq./kg PBS product.

GWP distribution seem to be the case of PLA product where S1 (100% composting) is the best scenario.

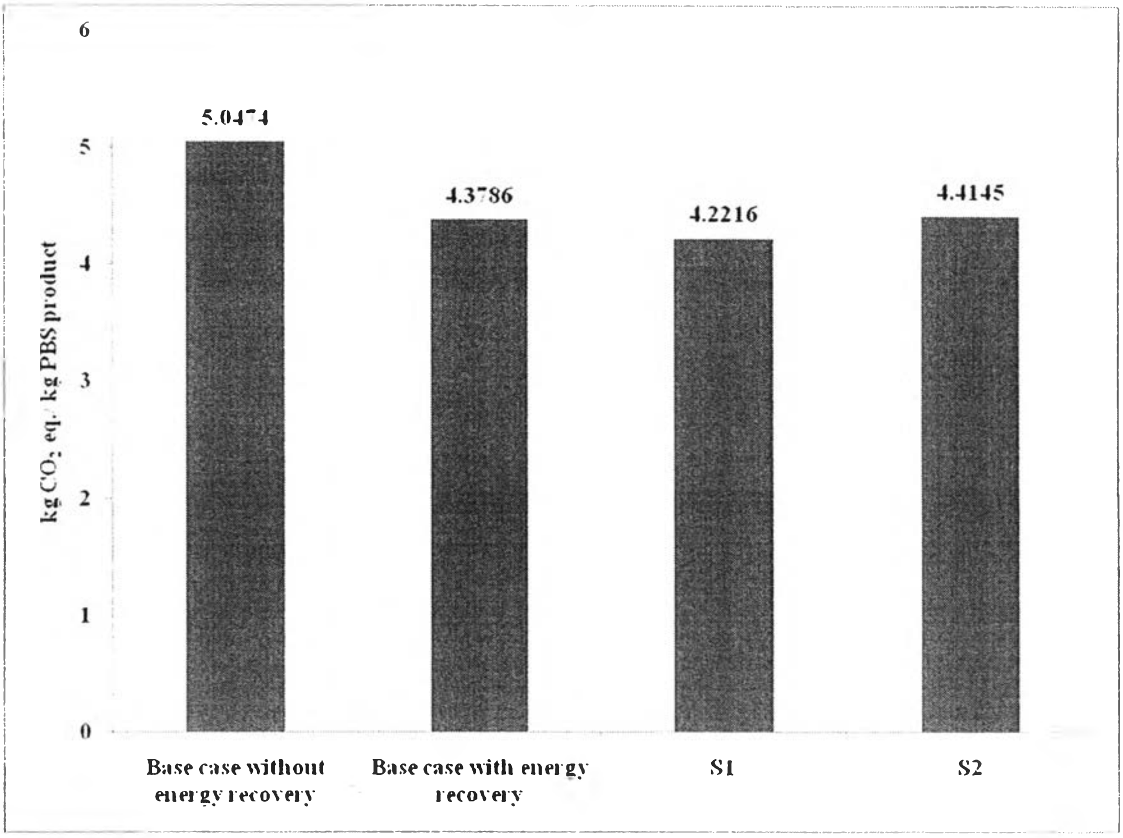


**Note: For S2, landfill with energy recovery is used in this scenario.*

Figure 4.25 Life cycle GWP of PBS T-shirt bag A by using CML 2 baseline 2000.

4.2.4.2.2 PBS Food Container

The life cycle GWP of PBS food container is shown in Figure 4.26. The base case without energy recovery has shown to have the highest impact of 5.0474 kg CO_2 eq./ kg PBS product while S1 (100% composting) has shown to be the best scenario which has lowest GWP of only 4.2216 kg CO_2 eq./kg PBS product.



**Note: For S2, landfill with energy recovery is used in this scenario.*

Figure 4.26 Life cycle GWP of PBS food container using CML 2 baseline 2000.

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 products. 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, PET, and PS were selected in this study to compare with

PLA and PBS based on the end products of interest in this study (T-shirt bag, drinking water bottle, and food container).

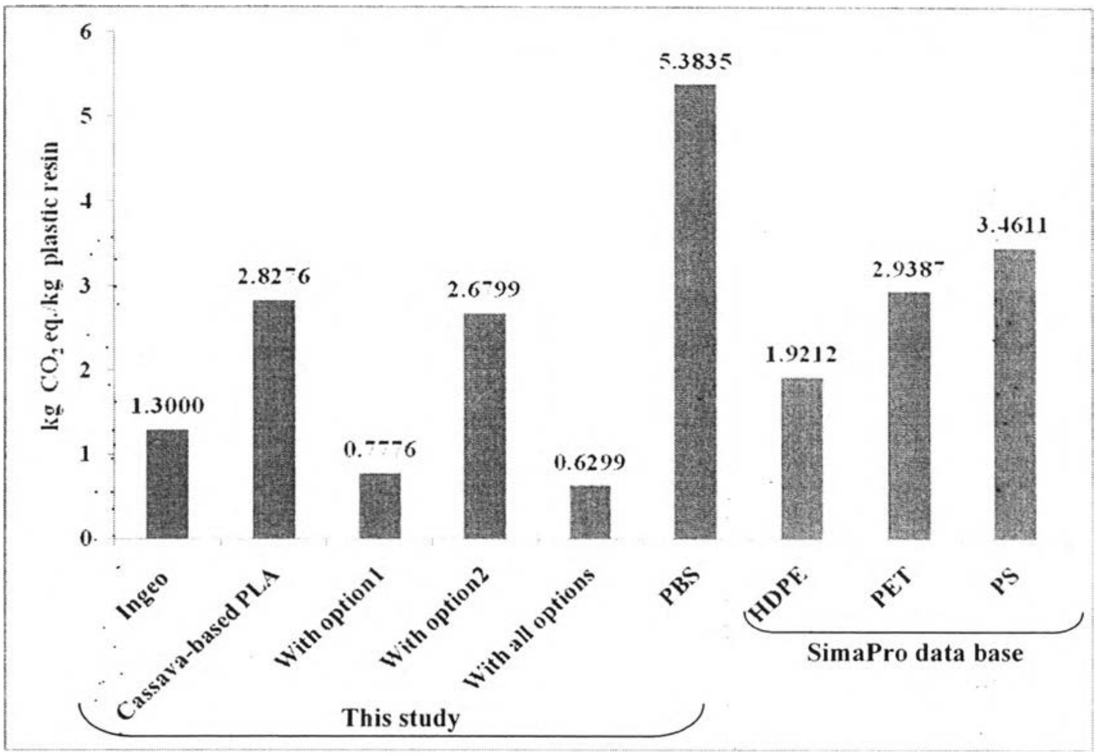


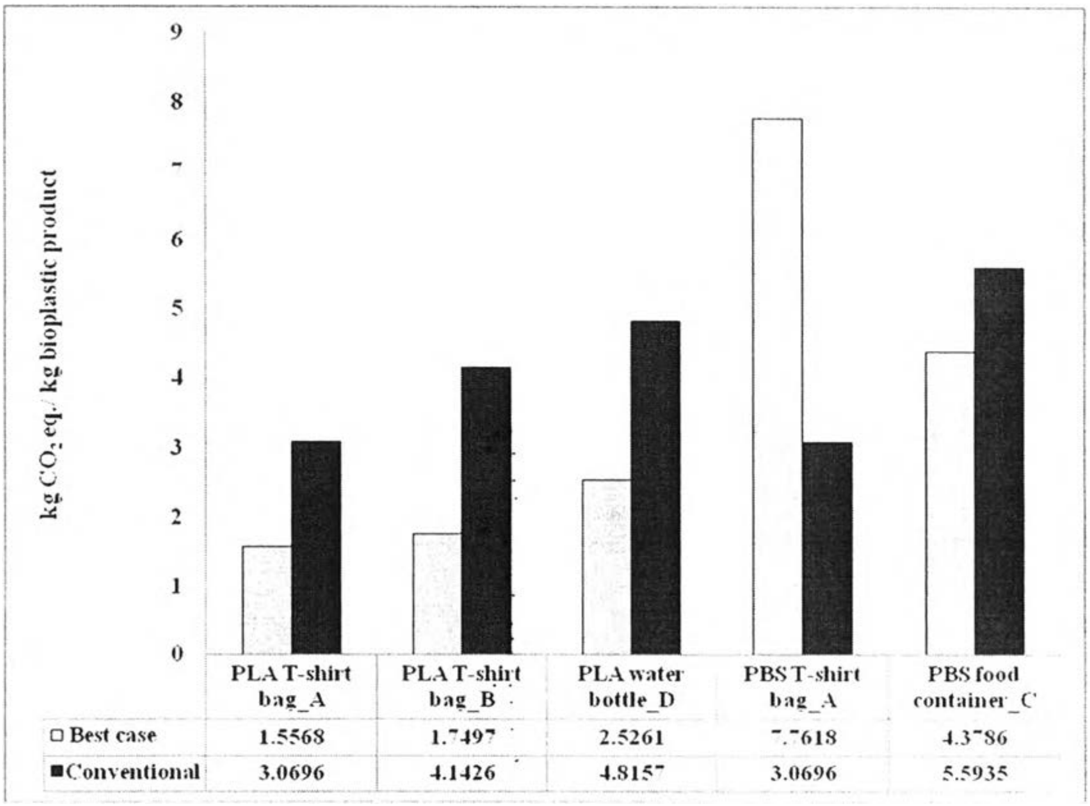
Figure 4.27 Comparison of the environmental performance of plastic resin (cradle-to-gate) based on one kilogram of plastic resin by using CML 2 baseline 2000.

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. The second highest GWP is Cassava-based PLA resin without any improvement options which has the GWP value comparable to those of conventional plastic resins. However, when both improvement options are taken into account, the GWP of Cassava-based PLA resin (with both options) is reduced significantly to only 0.6299 kg CO_2 eq. per kg resin. This GWP value is the lowest and much lower than GWP of conventional plastic resins (HDPE and PET) to be used to produce the same products (T-shirt bag and water bottle). When compared to commercial PLA resin "Ingeo", GWP of Cassava-based PLA resin (with both options) is about 50% of GWP of Ingeo as reported by Vink *et al.* (2010) of 1.3 kg CO_2 eq. per kg resin.

4.3.2 Cradle to Grave

In this part, the life cycle environmental performance of model bioplastic products produced from PLA and PBS were compared with the same products 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. The first part (the production of the resin) was already discussed in the previous section. For processing of the products, the best condition of processing phase was used in the analysis. For the disposal phase, the base case scenario with energy recovery (12% composting and 88% landfill with energy recovery) was used to evaluate bioplastic products. However, for conventional plastics, as they are not biodegradable or composable, they were assumed to be 100% treated by landfill. Figure 4.28 shows the comparison of the life cycle GWP between bioplastic products and conventional plastic products.

From this figure, it can be seen that the life cycle GWP values of bioplastic products are much lower than the values of conventional plastic products in most cases, except PBS T-shirt bag. Comparison between PLA and PBS for the same product, PLA has shown to have lower GWP than PBS which is due to the fact that approximately half PBS is still made from petroleum resource. For PBS food container, the GWP is less than PBS T-shirt bag on the same weight basis since PBS was not used 100% but it was mixed with PLA as mentioned previously. Thus, the impact was lower due the PLA content in the product.



	PLA T-shirt bag_A	PLA T-shirt bag_B	PLA water bottle_D	PBS T-shirt bag_A	PBS food container_C
□ Best case	1.5568	1.7497	2.5261	7.7618	4.3786
■ Conventional	3.0696	4.1426	4.8157	3.0696	5.5935

**Note: - For bioplastic product, best case of bioplastic production is used to compare with conventional plastic.*

- This comparison is base case scenario with energy recovery.

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