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Life Cycle Energy Consumption and Greenhouse Gas Emissions of Polylactic acid (PLA) and Polystyrene (PS) Trays

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ABSTRACT

This study aimed to assess the energy consumption and greenhouse gas (GHG) emissions of three types of materials used for tray production in Thailand. The materials studied were a polystyrene (PS) tray produced in Thailand and derived from petroleum, a polylactic acid (PLA-baseline) tray, which was produced in the USA and derived from corn, with the third one being a PLA tray with process improvement (PLA-improved). The improvements to the hypothetical PLA-improved tray included using PLA pellets produced in Thailand, using biomass feedstocks for PLA pellet production and reducing the amount of raw materials used in the forming process. The functional unit (FU) was 1,000 units of trays, with each tray being 20 × 14 × 1.5 cm. The first part of the study considered the production of PS trays, PLA trays (PLA-baseline) and PLA trays with process improvement (PLA-improved). The energy consumption and GHG emissions of PLA-improved trays was 51.38% and 63.2% lower than that of PS and PLA-baseline trays, respectively. Consequently, PLA-improved trays generated lower GHG emissions than PS trays by 16.04%, but the energy consumption to produce PLA-improved trays was slightly higher (4.06%) than that for PS trays.

In the second part of the study, different waste management scenarios using PS, PLA-baseline and PLA-improved trays were considered. It was found that incineration with energy recovery was suitable with PS trays because it could reduce energy consumption and GHG emissions by 22.7% and 3.4%, respectively, whereas, composting and landfill with energy recovery from methane collection were suitable with PLA-baseline and PLA-improved trays. Composting of PLA-baseline and PLA-improved trays produced a reduction in energy consumption of 6.5% and 12.0%, respectively, while GHG emissions were reduced by 267.7 and 253.9 kg CO_2 equivalent/FU, respectively. Landfill with energy recovery from methane collection from PLA-baseline and PLA-improved trays resulted in energy consumption reductions of 17.2% and 31.8%, respectively, with reductions in GHG emissions of 138.3 and 114.3 kg CO_2 equivalent/FU, respectively.

Keywords: polylactic acid, biodegradable tray, polystyrene, energy consumption, GHG emissions

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INTRODUCTION

Environmental problems are widespread throughout the world due to population and industrial growth, as well as a steady increase in the demand for food, energy and raw materials (Van Dam *et al*., 2005). Currently, the world is facing many challenges, such as increasing waste flows, energy depletion and climate change. In this context, biodegradable plastic products have a potential for energy savings, solid waste reduction and greenhouse gas (GHG) emissions reduction (Dornburg *et al*., 2006). Consequently, there is now a focus to develop biodegradable plastics derived from renewable resources, because they have higher savings potential than petroleum-based plastics (Iovino *et al*., 2008). In addition, global plastics production is more than 180 million tons per year and is increasing annually in terms of both supply and demand (Cutter, 2006). The solid waste resulting at the end of the use of the plastic products will accumulate in the environment.

The global demand for biodegradable plastics is estimated to be 0.8-1.3 million tonne per year in 2010. However, there was a limited supply of 0.08 million tonne per year in 2007 (TBIA, 2007). There are high amounts of agricultural resources in Thailand, such as rice, cassava, corn, and sugarcane (AOE, 2008), which can be used as feedstock for biodegradable plastics, including polylactic acid (PLA), polyhydroxyalkanoates (PHAs) and thermoplastic starch (TPS). In addition, municipal solid waste (MSW) in Thailand has steadily increased (PCD, 2007). Between 2002 and 2007, MSW generation increased from 38,000 to 40,322 ton/day. Plastics waste accounts for 15.8% of total MSW (PCD, 2007). Because of these problems, biodegradable plastics are an alternative material that can reduce the solid waste generated from petroleum-based plastics. Therefore, not only would a new plant to produce biodegradable plastic in Thailand support both the global demand and local demand, but it would also be advantageous for MSW management in Thailand. Presently, PLA, one of biodegradable plastics, has high economic potential for consumer applications, including, for example, agricultural plastics, diapers and electric appliances, with approximately 70% of PLA used for packaging applications (Dornburg *et al*., 2006). PLA is a synthetic biopolymer polyester derived from agricultural products. It is normally derived from biomass, such as corn, cassava or sugarcane (Vink *et al*., 2003). Consequently, in Thailand, there is a plan for the first commercial PLA production plant with a capacity of 10 thousand tonne per year (TBIA, 2007). Process improvement for PLA pellets production becomes more attractive because of its several benefits, such as lower energy and materials consumption and lower air emissions. For example, whole part of crops can be used as biomass feedstocks, via with the bio-refinery integrated process (Vink *et al*., 2003), and triple-effect evaporation (Paoluglam, 2005) used for PLA production. For waste management, the conversion of MSW to energy or a product utilizing an environmentally friendly technique can be achieved through composting (Razza *et al*., 2009), landfill with gas collection for electricity generation (Paoluglam, 2005) and incineration with energy recovery (Molgaard, 1995).

In the current study, the aims were to assess energy consumption and GHG emissions of PLA and PS trays, in the processes of raw materials extraction, manufacturing and transportation. The influence of an improved process for PLA trays was also investigated. The various end-of-life management options were considered for MSW package waste. In addition, environmentally friendly assessments were performed to provide information for MSW management policy. The methodology of the analysis used the life cycle assessment (LCA) technique.

MATERIALS AND METHODS

Methodology

The LCA methodology is described in the standard EN ISO 14044 (2006). The calculation of energy used and GHG emissions using the methodology are described below.

Scope and system boundary

The investigation of PLA and PS trays included manufacturing and waste management. Four phases in the life cycle of trays were considered: raw materials extraction, manufacturing, transportation and end of life management. The functional unit (FU) in this study was 1,000 units (each 20 × 14 × 1.5 cm) of PLA-baseline, PLA-improved and PS trays. There were three trays weights of 15.10, 13.59 and 4.03 grams per tray, respectively. The system boundary for the study is illustrated in Figure 1. The investigation was based on the Electricity Generating Authority of Thailand data of 2007. Fuels used for electricity in Thailand include natural gas, oil and coal. This study was divided into two parts. Firstly, the life cycle energy consumption and GHG emissions generated in the process from raw materials to tray production (cradle-to-gate) were investigated. Secondly, the end of life management was added to investigation (cradle-to-grave).

PS and PLA trays baseline

In this study, the life cycle inventory (LCI) data of PS trays included: raw materials production (styrene monomer, ethyl benzene, naphtha, polybutadiene rubber and peroxide) and polystyrene production to produce the formulated pellets of general purpose polystyrene (GPPS) and high impact polystyrene (HIPS). Thermoforming techniques were used to produce the PS trays. The LCI data on the raw materials production phase were collected from a database of SimaPro 7's LCA software. GPPS and HIPS data were supplemented from Paoluglam (2005) based on production in 2005. LCI data on PS tray production were sourced from the manufacturing of PS trays in Thailand during 2007.

The LCI data on PLA trays (PLA-baseline) included corn production, PLA pellets production (dextrose, lactic acid, and PLA production) and thermoforming techniques used to produce the PLA trays. Corn production data were collected from a database of SimaPro 7's LCA software. The PLA pellets production data were supplemented from Vink *et al*. (2003) based on production in 2003. The PLA pellets were supplemented from Cargill Dow at the Blair, Nebraska. The amounts of raw materials and energy used from PLA pellets production were expressed in units of electricity and natural gas at

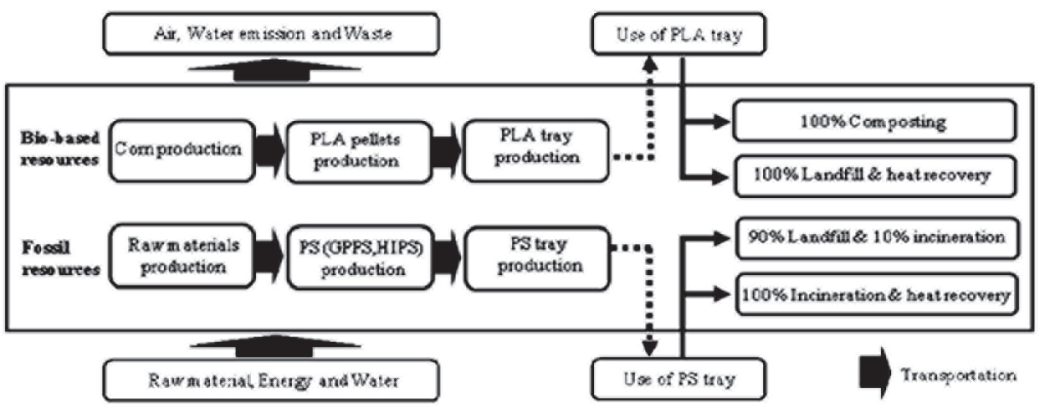


Figure 1 System boundary of the study of PS and PLA trays with end of life management.

a ratio of 1:1 (Johansson, 2005). LCI data on PLA tray production were obtained from the National Metal and Materials Technology Center (MTEC). In addition, LCI data were collected from a pilot-scale plant manufacturing PLA trays in 2007. Data on distances was supplemented from the Department of Highways and Paoluglam (2005). The LCI data on end of life management for composting was supplemented from experiments. The LCI data on landfill, landfill with energy recovery from methane collection, incineration and incineration with energy recovery were collected from Molgaard (1995) and Bohlmann (2004).

PLA trays with process improvement (PLA-improved)

The improvements in a hypothetical PLA-improved process included: using PLA pellets production in Thailand (Pathumtani province), using biomass feedstocks for PLA pellets production (Vink *et al*., 2003) and reducing the amount of raw material used in the forming process by 10% (Tan and Khoo, 2005). Biomass feedstocks for PLA pellets included all parts of crops and residue waste from PLA pellets production.

Energy consumption

This impact category was evaluated in MJ per functional unit. The indicators relating to the energy content of different energy sources are shown in Table 1.

GHG emissions

Greenhouse gases emitted by fossil fuels and electricity generation were used to evaluate the GHG emissions. This study included emissions of the four major GHG: carbon dioxide (CO_2), methane (CH_4); nitrous oxide (N_2O) and carbon monoxide (CO). Concerns about potential global warming effects of major greenhouse gases have led to recognition of the need to reduce anthropogenic GHG emissions. According to the Intergovernmental Panel on Climate Change (IPCC), GHG can remain in the atmosphere for 100 years, a period generally accepted as the mean atmospheric residence time of the most volumetrically significant greenhouse gases. The GHG emissions are defined in the form of CO_2 equivalent. Equation 1 was used to determine the amount of GHG emissions in the study:

$$GHG = \sum_{g}(GWP_g \times E_g) \quad (1)$$

where, GHG is the GHG emissions per functional unit (kg CO_2 eq./functional unit)

g is the subscript to indicate the greenhouse gas (CO_2, CH_4, N_2O, and CO)

E_g is the amount of greenhouse gas g per

Table 1 Net calorific value of different energy sources.

Energy	Unit	Net calorific value	Reference
Coal	MJ/L	26.37	(DEDE, 2007)
Crude oil	MJ/ L	36.33	(DEDE, 2009a)
Diesel oil	MJ/ L	36.42	(DEDE, 2007)
Heavy oil	MJ/ L	39.77	(DEDE, 2009a)
Light oil	MJ/ L	34.53	(DEDE, 2007)
Natural gas	MJ/ kg	33.07	(DEDE, 2007)
Refinery gas	MJ/kg	54.80	SimaPro 7.0
Residual oil	MJ/ L	40.60	SimaPro 7.0
Naphtha	MJ/ kg	44.93	(Argonne National Laboratory, 2008)
Butane	MJ/kg	45.27	(Argonne National Laboratory, 2008)
Electricity	MJ/kWh	3.6	(DEDE, 2009a)

functional unit (kg GHG_g/functional unit) GWP_g is the Global Warming Potential of greenhouse gas g (a relative value of 1 for CO_2, 23 for CH_4, 296 for N_2O, and 1.57 for CO (IPCC, 2001)).

RESULTS AND DISCUSSION

Life cycle inventory results (cradle-to-gate)

Details of LCI data from cradle to gate for PS, PLA-baseline and PLA-improved trays are shown in Tables 2, 3 and 4, respectively.

End of life management

Four options were considered as waste treatment scenarios: 1) 90% landfill and 10% incineration for both PS and PLA trays; 2) 100% incineration with energy recovery for PS; 3) 100% composting; and 4) 100% landfill with energy recovery from methane collection for PLA.

Option 1: 90% landfill and 10% incineration (PS and PLA)

About 90% all municipal solid waste (MSW) in Thailand is disposed of in landfill, with incineration accounting for the remaining 10% (Paoluglam, 2005). The LCI data on landfills was obtained from Bohlmann (2004). This study presumed that polymer (PS) was not decomposed, while PLA was completely degradable in the landfill (Bohlmann, 2004). The landfill gas generation for PLA included CO_2 and CH_4 emissions with a ratio of 10:90, respectively (Bohlmann, 2004). The LCI data on the

Table 2 Material input-output, energy consumption and GHG emissions per functional unit of PS trays (cradle-to-gate).

	Raw mat. production	PS production	Tray production	Transportation	Total
Input					
Total energy consumption, (MJ)	4.327E+02	9.925E+01	2.910E+01	2.618E+00	5.636E+02
Coal, (MJ)	1.307E+00	3.064E+01	3.841E+00	1.147E-04	3.579E+01
Crude oil, (MJ)	1.329E+00	-	-	-	1.329E+00
Diesel oil, (MJ)	-	-	-	2.505E+00	2.505E+00
Heavy oil, (MJ)	1.719E+00	1.115E+00	2.537E-01	1.126E-01	3.45E+00
Light oil, (MJ)	7.168E-05	2.885E-03	2.170E-03	-	5.13E-03
Natural gas, (MJ)	6.119E+00	6.749E+01	7.475E+00	2.542E-04	8.10E+01
Residual oil, (MJ)	3.634E+01	-	-	-	3.63E+01
Refinery gas, (MJ)	8.934E+01	-	-	-	8.93E+01
Naphtha, (MJ)	2.965E+02	-	-	-	2.96E+02
Butane, (MJ)	-	-	1.753E+01	-	1.753E+01
Output					
Products, (kg)	*Raw material	**PS	4.03	-	4.03
CO_2 emissions, (kg)	1.20E+01	1.51E+01	2.13E+00	5.37E-01	2.80E+01
CH_4 emissions, (kg)	5.08E-02	1.24E-03	1.19E-03	3.59E-04	5.36E-02
CO emissions, (kg)	7.51E-03	5.71E-03	1.56E-03	1.56E-03	1.56E-02
N_2O emissions, (kg)	1.45E-04	6.16E-04	7.07E-06	7.07E-06	8.26E-04

Note: *Raw material production includes styrene monomer, ethyl benzene, naphtha, polybutadiene rubber and peroxide.
** PS pellets includes GPPS pellets (93.5%) and HIPS (6.5%).

Table 3 Material input-output, energy consumption and GHG emissions per functional unit of PLA-baseline trays (cradle-to-gate).

	Corn production	PLA production	Tray production	Transportation	Total
Input					
Total energy consumption, (MJ)	1.238E+02	9.022E+02	1.076E+02	7.474E+01	1.208E+03
Coal, (MJ)	5.207E+00	1.473E+02	3.108E+01	-	1.836E+02
Crude oil, (MJ)	_	-	-	-	-
Diesel oil, (MJ)	3.143E+01	-	-	4.472E+01	7.615E+01
Heavy oil, (MJ)	1.240E+01	1.412E+00	1.695E+00	3.004E+01	4.555E+01
Light oil, (MJ)	_	4.113E-02	1.233E-06	-	4.113E-02
Natural gas, (MJ)	7.478E+01	7.535E+02	7.484E+01	-	9.031E+02
Output					
Products, (kg)	29.64	17.71	15.10	-	15.10
CO_2 emissions, (kg)	-8.69E+01	9.31E+01	2.17E+01	1.12E+01	3.93E+01
CH_4 emissions, (kg)	1.98E-02	8.09E-02	2.13E-03	7.96E-03	1.11E-04
CO emissions, (kg)	2.57E-02	3.70E-02	6.22E-03	2.04E-02	8.93E-02
N_2O emissions, (kg)	1.93E-04	3.01E-03	6.47E-04	1.45E-04	4.00E-03

Table 4 Material input-output, energy consumption and GHG emissions per functional unit of PLA-improved trays (cradle-to-gate).

	Corn production	PLA production	Tray production	Transportation	Total
Input					
Total energy consumption, (MJ)	1.134E+02	3.619E+02	1.076E+02	4.582E+00	5.875E+02
Coal, (MJ)	4.686E+00	6.305E+01	3.108E+01	-	9.882E+01
Crude oil, (MJ)	-	-	-	-	-
Diesel oil, (MJ)	2.829E+01	-	-	4.582E+00	3.287E+01
Heavy oil, (MJ)	1.116E+01	3.267E+00	1.695E+00	-	1.613E+01
Light oil, (MJ)	_	3.737E-02	1.233E-06	-	3.738E-02
Natural gas, (MJ)	6.930E+01	2.955E+02	7.484E+01	-	4.397E+02
Output					
Products, (kg)	26.67	16.10	13.59	-	13.59
CO_2 emissions, (kg)	-4.63E+01	3.79E+01	2.17E+01	6.64E-01	1.39E+01
CH_4 emissions, (kg)	1.79E-02	3.04E-02	2.13E-03	4.41E-04	4.68E-02
CO emissions, (kg)	2.31E-02	1.54E-02	6.22E-03	1.99E-03	2.05E-03
N_2O emissions, (kg)	1.74E-04	1.22E-03	6.47E-04	8.75E-04	5.44E-02

incineration of PS was sourced from Molgaard (1995). The LCI results show that PS contributed zero GHG emissions in the landfill (Table 5).

Option 2: Incineration with energy recovery (PS)

The LCI data on incineration and heat recovery was sourced from Molgaard (1995). Energy consumption analysis for running the incineration plant was supplemented with Thailand Electricity data.

The energy recovery from the incineration plant per functional unit of plastic waste in equivalent amounts of crude oil, natural gas and coal products is shown in Table 6.

Option 3: Composting (PLA)

The biodegradability potential of PLA was determined under aerobic degradation conditions, as per ISO 14855-99. The testing inoculums (soil) were obtained from the compost of organic agricultural waste. The test mixtures used inoculums and test material (PLA), in the ratio 6:1. The composting process utilizes air from the environment to decompose the plastic. As composting is an aerobic biological treatment, it presumes that CH_4 emissions are not generated. The results showed that the biodegradability potential of PLA was 86.82% of CO_2 evolution. The bonuses obtained from a composting treatment for agricultural use include fertilizers (N-

Table 5 Energy consumption and GHG emissions from 90% landfill and 10% incineration per kg of PLA and PS trays.

	Energy (MJ)	GHG emissions (kg)			
		CO_2	CH_4	CO	N_2O
PLA-baseline					
- Incineration	2.718	2.29E-01	7.16E-06	6.38E-05	7.04E-06
- Landfill	-	2.56E+00	8.41E+00	-	-
PLA-improved					
- Incineration	2.446	2.06E-01	6.44E-06	5.75E-06	6.33E-06
- Landfill	-	2.31E+00	7.57E-01	-	-
PS					
- Incineration	0.725	5.32E+00	8.62E+00	3.84E-04	1.56E-05
- Landfill	-	-	-	-	-

Table 6 Input-output energy and GHG emissions from incineration and energy recovery per functional unit of PS trays.

Input			Output		
Type	Amounts	Unit	Type	Amounts	Unit
Electricity	0.202	kWh	Crude oil	3.23E-01	kg
			Natural gas	2.70E+00	kg
			Coal	1.00E+00	kg
			CO_2 emissions	1.29E+01	kg
			CH_4 emissions	1.67E-05	kg
			CO emissions	9.19E-04	kg
			N_2O emissions	3.29E-05	kg

P-K), and carbon sequestration (Razza *et al*., 2009). Carbon sequestration based on the organic carbon of the compost amounted to 11.26%. The LCI data on composting obtained from PLA-baseline and PLA-improved trays are shown in Table 7.

Option 4: Landfill with energy recovery from methane collection (PLA)

In Thailand, plastics are currently disposed of in landfill. The data in the current study were sourced from Bohlmann (2004). Landfill gas generation included CO_2 and CH_4 emissions in the ratio 10:90 (Bohlmann, 2004). The energy recovery for electricity generation was derived from 75% of the CH_4 emissions. The LCI results of the calculation are summarized in Table 8.

Life cycle assessment results I (cradle-to-gate)

The cradle-to-gate LCA study investigated the results from the combination of the production phases. The results of energy consumption and GHG emissions in the production phase of the two types of tray packaging are shown in Figures 2 and 3, respectively.

For energy consumption (Figure 2), the main load came from the production of the PLA-baseline trays, which was approximately 53.5% higher than that of the PS trays. For PLA-baseline trays, the use of natural gas and electricity in the PLA pellets production resulted in energy consumption of 74.6%. For the PS trays, the total energy consumption from raw materials extraction was 76.7%. The energy used for GPPS pellets was

Table 7 Input-output data of composting obtained from 15.10 kg of PLA-baseline and 13.59 kg of PLA-improved.

Type	Amounts		Unit
	PLA-baseline	PLA-improved	
Input			
Organic waste	90.60	81.54	kg
PLA	15.10	13.59	kg
Air	*76.81	*69.12	kg
Output			
Compost	99.65	89.68	kg
- Carbon sequestration	11.22	10.09	kg
- Fertilizer N (1.43%)	0.996	0.986	kg
- Fertilizer P (0.60%)	0.597	0.538	kg
- Fertilizer K (0.66%)	0.657	0.592	kg
CO_2 emissions	22.18	19.97	kg

Note: *For PLA-baseline, air consisted of oxygen (16.13 kg) and nitrogen (60.68 kg).
**For PLA-improved, air consisted of oxygen (14.51 kg) and nitrogen (54.61 kg).

Table 8 Input-output data of landfill with energy recovery from methane collection obtained from 15.10 kg of PLA-baseline and 13.59 kg of PLA-improved.

Cases	Input	Output		
	PLA (kg)	CO_2 emission(kg)	CH_4 emission(kg)	Electricity (kWh)
PLA-baseline	15.10	2.57	2.10	57.92
PLA-Improved	13.59	2.31	1.89	52.13

78.4 MJ/kg, while that of HIPS pellets was 81.3 MJ/kg. The proportionally higher usage of GPPS (up to 93.5%) in the tray forming step could greatly reserve energy. Moreover, PS consumed fewer raw materials (4.03 g/tray).

There were four major causes of the lower energy consumption in the PLA-improved process. Firstly, since the PLA pellets production plant is located in Thailand, the reduced transportation distance reduced fossil energy consumption of diesel oil to 40.1 MJ and heavy fuel oil to 30.0 MJ. Secondly, using biomass feedstock for PLA pellets production resulted in a saving of natural gas and electricity consumption of 493.3 MJ, which was 40.6% lower than that used for PLA-baseline production. Thirdly, the improvements reduced material consumption by 10%, which resulted in a reduction of energy from the base case by 9.5% accounting for 115.3 MJ. Therefore, the PLA-improved process had 51.4% lower energy consumption than the PLA-baseline process. However, the energy used for the PLA-improved process was slightly higher (4.06%) than for PS trays, mainly due to the energy consumption in PLA pellets production of 61.6 %

The results of the GHG emission analysis for each type of tray are shown in Figure 3. The highest GHG emission in the PLA-baseline process came from PLA pellets production, which was 31.63% higher than for PS trays. In the PLA-baseline process, PLA pellets production generated 74.18% of total GHG emissions because of the large amount of natural gas and electricity consumption. However, corn growing absorbed GHG emissions of 2.095 kg CO_2 equivalent/kg corn (CCAN, 2009), which resulted in a substantial

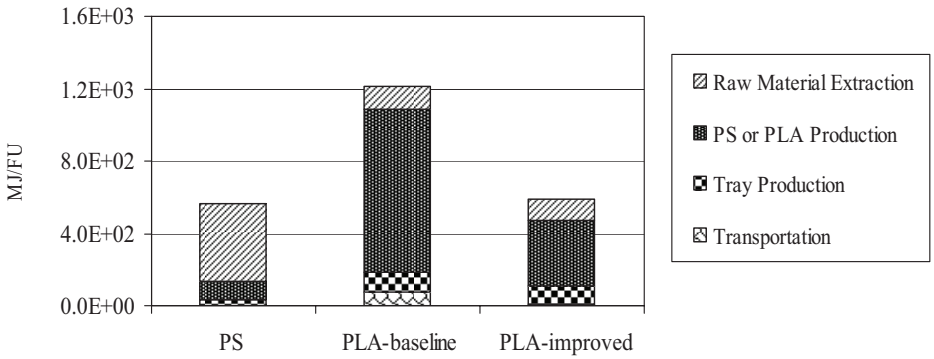


Figure 2 Energy consumption in MJ per functional unit of PLA and PS trays (cradle-to-gate).

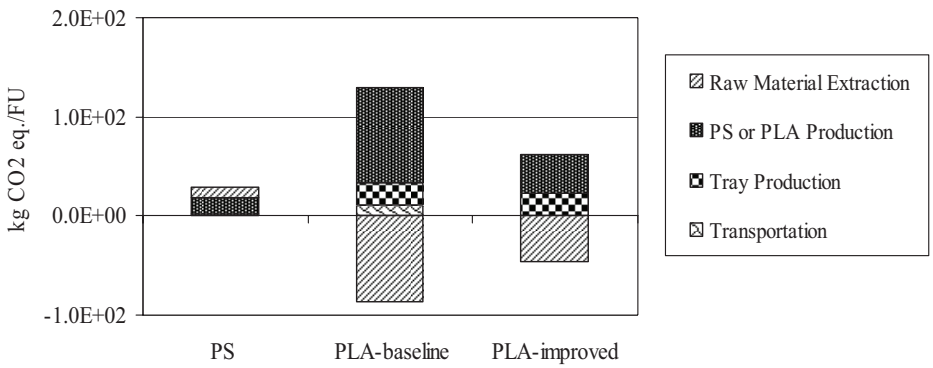


Figure 3 GHG emissions per functional unit of PLA and PS trays (cradle-to-gate).

decrease in total GHG emissions for the PLA-baseline process (69.5%). With the addition of improvements, the PLA-improved process had 16.04% lower GHG emissions than for PS trays. Consequently, it also had a GHG reduction of 27.28 kg CO_2 equivalent/FU from the base case.

Life cycle assessment results II (cradle-to-grave)

In the cradle-to-grave LCA study, the results from the whole life cycle including end of life management were investigated. The results of life cycle energy consumption and GHG emissions for two the types of packaging are shown in Figures 4 and 5, respectively.

The comparison of energy consumption is shown in Figure 4. The PLA-improved process together with landfill with energy recovery from methane collection (option 4) showed the best energy consumption of 400.8 MJ/FU. The energy produced from methane collection led to preserving energy from the production of PLA-improved trays by 31.8%, accounting for 187.7 MJ/FU. In addition, the PLA-improved process with composting showed good results. As mentioned above, the fertilizer products from composting treatment reduced the energy used by 12.1%, which accounted for 70.9 MJ/FU. The PS trays process with incineration and heat recovery was also a favorable option due to the energy produced from incineration (128.1 MJ/FU), producing 22.7 % energy conservation in the production of PS trays.

The comparison of life cycle GHG emissions is shown in Figure 5. The PLA-improved process with composting was the best option with -251.5 kg CO_2 equivalent/FU because of carbon sequestration and fertilizer (N-P-K)

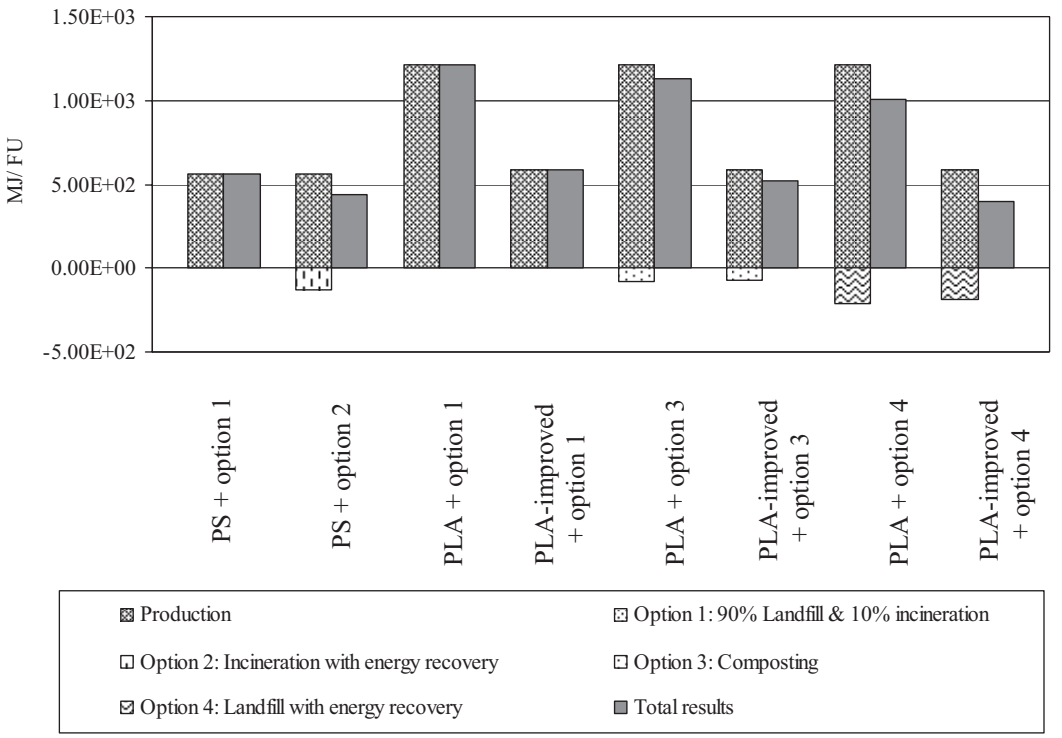


Figure 4 Life cycle energy consumption in MJ per functional unit of PLA and PS trays (cradle-to-grave).

products. It resulted in a GHG reduction of 267.34 kg CO_2 equivalent/FU. In addition, the PLA-improved process with landfill with energy recovery from methane collection also produced a good result, as it contributed a GHG reduction of 114.3 kg CO_2 equivalent/FU. The GHG emissions obtained from the electricity generated using fossil fuels could be replaced by electricity generation from the landfill with energy recovery from methane collection. Accordingly, the negative values of GHG reduction are shown in Figure 5.

Option 1 was the worst scenario for GHG emissions for PLA and PS, where plastic waste was disposed of in landfill (90%) and incinerated (10%). The main emissions came from the high amount of landfill gas emission of PLA and the high amount of combustion emission from the incineration of PS. Although disposal of PS trays by landfill does not have any GHG emission, there are other impacts to the environment that were not considered in the scope of this study.

Comparison with other studies (cradle-to-gate)

The energy consumption per kg of HIPS, GPPS, PLA pellets and biomass feedstock for PLA pellets production were within the range of the data obtained from other sources, as shown in Table 9. The GHG emissions per kg of both types of PLA pellets were consistent with values in the literature. The GHG emissions per kg of GPPS were substantially higher than in the literature, as shown in Table 10, due to the high GHG emissions of electricity (0.56 kg CO_2 eq./kWh) in Thailand (DEDE, 2009b).

As mentioned above, GHG emissions per kg of GPPS pellets were considered. The results

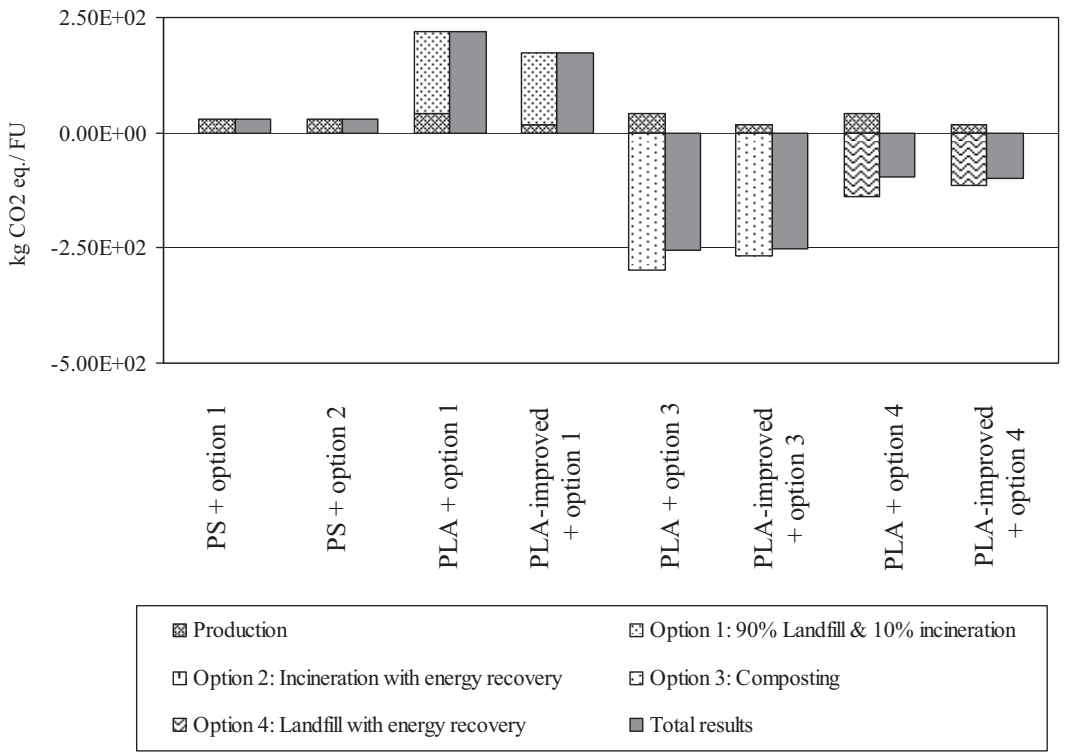


Figure 5 Life cycle GHG emissions in kg CO_2 equivalent per functional unit of PLA and PS trays (cradle-to-grave).

Table 9 Comparison of energy consumption of HIPS, GPPS and PLA pellets with other studies (Unit: MJ/kg).

	This study	SimaPro 7 (2008)	PlasticsEU (2008)	Hisun Co.,Ltd (2006)	Bohlmann (2003)	Vink *et al.* (2003)
HIPS	81.32	86.10	87.20	-	-	-
GPPS	78.41	82.10	87.20	-	-	-
PLA	54.08	-	-	64.13	51.00	54.10
*PLA	29.61	-	-	-	-	29.2

* PLA used biomass feedstock for PLA pellets production.

Table 10 Comparison of the GHG emissions of HIPS, GPPS and PLA pellets with other studies (Unit: kg CO_2 eq./kg).

	This study (2008)	SimaPro 7 (2008)	PlasticsEU (2008)	Hisun Co.,Ltd (2006)	Bohlmann (2003)	Vink *et al.* (2003)
HIPS	3.76	2.92	3.46	-	-	-
GPPS	3.74	2.72	3.46	-	-	-
PLA	2.53	-	-	1.62	2.71	1.8
*PLA	-0.41	-	-	-	-	-0.3

* PLA used biomass feedstock for PLA pellets production.

show that the GHG emissions caused by raw materials were 1.51 kg CO_2 equivalent and by production were 2.23 kg CO_2 equivalent. The electricity used in the production of GPPS pellets was the main source (98.7%) of the GHG emissions in the GPPS pellets production.

CONCLUSIONS

The PLA-improved process produced the best results. The GHG emissions of the PLA-improved process were the lowest, but the energy used was slightly higher than for PS trays. Different waste management scenarios for both PLA and PS trays were considered. The results showed that composting or landfill with energy recovery from methane collection was suitable for PLA trays, while incineration with energy recovery was also appropriate for PS trays. Additionally, not only the energy recovery from landfill and incineration, but also the products from composting led to energy and GHG reductions in the production process.

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