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THESIS

MODELING AND LIFE CYCLE ENVIRONMENTAL ASSESSMENT OF CONVENTIONAL AND DEGRADABLE PLASTIC PACKAGES

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A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
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The first objective of this study is to assess environmental impact associated with two types of packages using the Life Cycle Assessment technique. The materials of trays package are Polylactic acid (PLA) and Polystyrene (PS) while the materials of garbage bags package are PE/starch blend (PE/starch), PE/Total degradable plastic additive blend (PE/TDPA) and conventional Polyethylene (PE). The functional unit is specified as 420 liters of 20 x 14 x 1.5 cm. of PLA and PS trays which weights 15.10 and 4.03 kilograms, respectively. For garbage bags, the function unit is 500,000 liter of 58.4 x 95.25 cm. for PE/starch, PE/TDPA and PE bags which weight 416.83, 93.17 and 60.83 kilograms, respectively. The system boundary is from raw material extraction to waste management. The Life Cycle Impact Assessment was done by using Microsoft Excel and the SimaPro 7.02 program together with the CML 2 Baseline 2000 version 2.03 method. It is found that trays' production and transportation to consumers, the energy consumption and environmental impact of PLA trays is 1.88 times and 2.57 times more than the PS trays, respectively. As mentioned above, the highest portion comes from electricity and natural gas used in PLA production for PLA trays and raw material extraction for PS trays. The main environmental impacts are marine aquatic ecotoxicity, human toxicity and global warming. For waste management, the results show that incineration and heat recovery is suitable for both PLA and PS trays while composting or landfill with energy recovery from methane collection is also appropriate for PLA trays. For garbage bags, it is found that during the garbage bags' production and transportation to consumers, the energy consumption and environmental impact of PE/starch garbage bags is the highest of all materials studied due to high consumption of virgin PE pellets. The highest energy consumption and environmental impact come from raw material extraction for all garbage bags. For waste management, the results show that incineration and heat recovery is the most suitable for garbage bags, while landfill with energy recovery from methane collection is appropriate as well.

The second objective of this study is to propose and evaluate the kinetics of C-CO_2 evolution during biodegradation of plastic materials including PE, microcrystalline cellulose (MCE), PE/starch, and PLA. The aerobic biodegradation under controlled composting conditions was monitorated according to ISO 14855-99. It is found that the first order reaction in series with a flat lag phase model is desirable for MCE, PE/starch and PLA.

Student's signature	Thesis Advisor's signature	___ / ___ / ___

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Unchalee Suwanmane
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LIST OF ABBREVIATIONS

C_{T_t} = Percentage of cumulative C-CO_2 product at time t

C_{r_t}, = Percentages of readily hydrolysable solid carbon fractions at time t

C_{m_t} = Percentages of moderately hydrolysable solid carbon fractions at time t

C_{s_t} = Percentages of slowly hydrolysable solid carbon fractions at time t

C_{aq_t} = Percentage of intermediate solid carbon fraction at time t

C_{C0} = Percentage of total initial carbon

C_{r0}, = Percentage of initial readily hydrolysable solid carbon fraction

C_{m0} = Percentage of initial moderately hydrolysable solid carbon fraction

C_{s0} = Percentage of initial slowly hydrolysable solid carbon fraction

C_{aq0} = Percentage of initial intermediate solid carbon at time t

C_{FC} = Percentage of total final carbon

C_{rfinal} = Percentage of final readily hydrolysable solid carbon

C_{mfinal} = Percentage of final moderately hydrolysable solid carbon

C_{sfinal} = Percentage of final slowly hydrolysable solid carbon

$C_{aqfinal}$ = Percentage of final intermediate solid carbon

c = lag time (day)

k_{hr} = Readily hydrolysis rate constant (day^{-1})

k_{hm} = Moderately hydrolysis rate constant (day^{-1})

k_{hs} = Slowly hydrolysis rate constant (day^{-1})

k_{aq} = Mineralization rate constant (day^{-1})

kg = kilogram

EPS = Expandable Polystyrene

FU = Functional unit

GHG = Greenhouse Gas

GPPS = General Purpose Polystyrene

GWP = Global Warming Potential

LIST OF ABBREVIATIONS (Continued)

HDPE = High Density Polyethylene
HIPS = High Impact Polystyrene
LCA = Life Cycle Assessment
LCI = Life Cycle Inventory
LCIA = Life Cycle Impact Assessment
LDPE = Low Density Polyethylene
LLDPE = Linear Low Density Polyethylene
MCE = Microcrystalline cellulose
m^2 = Square meter (m^2)
PE = Polyethylene
PE/starch= PE/starch blend
PLA = Polylactic acid
PS = Polystyrene
Pt. = Person Equivalent
TDPA = Totally Degradation Plastic Additive
t = time (day)

MODELING AND LIFE CYCLE ENVIRONMENTAL ASSESSMENT OF CONVENTIONAL AND DEGRADABLE PLASTIC PACKAGES

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, our world is facing many challenges such as increasing waste flows, energy depletion and climate change. In addition, the global plastics production is more than 180 millions tons per year, increasing annually in supply and demand (Cutter, 2006). The solid waste after the end of life will accumulate in the environment. In this context, biodegradable plastics 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 potential than petroleum-based plastics (Iovino *et al.,* 2008).

The global demand for biodegradable plastics is approximately 0.8-1.3 million tonnes per year in 2010, however, there are limited supply of 0.08 million tonnes per year in 2007 (TBIA, 2007). In Thailand, there are high amount of agricultural resources such as rice, cassava, corn, and sugarcane (AOE, 2008). The resources can be used as feedstock for biodegradable plastics e.g. polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and thermoplastic starch (TPS). Besides, the municipal solid waste (MSW) in Thailand has steadily increased. Between 2002 and 2007, the MSW generation increased from 38,000 to 40,322 ton/day. Plastics waste accounts for 15.8% of total MSW (PCD, 2007). Hence, biodegradable plastics can be alternative materials that reduce MSW from petroleum-based plastics. Process improvement for biodegradable plastics production becomes more attractive because of its several benefits on lower air emission, lower energy & materials consumption.

Wind power replaced grid electricity, biomass feedstock derived from whole part of crops, bio-refinery integrated process (Vink *et al.,* 2003), and triple-effect evaporation (Paoluglam, 2005) were used for bioplastics production. The change of MSW to energy or product with environmental friendly techniques such as composting (Razza *et al.,* 2009), landfill with methane gas collection for electricity generation (Paoluglam, 2005), and incineration with energy recovery (Molgaard, 1995) were also introduced.

Degradation is an important process in the environmental breakdown of polymer substrate into organic waste (Tosun *et al.,* 2008). Composting is an alternative for degradable materials to replace conventional disposal method, landfill or incineration. Biodegradable waste or organic matters can degrade into humic substance, which is recognized as a high quality of fertilizer for agricultural process (Ganjyal *et al.,* 2007). Moreover, municipal solid waste (MSW) management by composting is an environmental friendly method because it can reduce material in the waste stream and save of energy, etc.

Recently, composting kinetic to describe the decomposition of organic waste is studied. The parameters obtained from the model analysis are useful to estimate the carbon (C) mineralization of several organic materials (Komilis, 2006). Degradation curve of the carbon dioxide production from composting consists of three stages including lag phase, growth phase, and stationary phase (Hamid, 2000). Several kinetic models were studied under control composting conditions. It is concluded that degradation of solid carbon to carbon dioxide is first order kinetic (Molina *et al.,* 1980; Jones, 1984; Bonde and Rosswall, 1987; Murwira, 1990; Komilis, 2006). However, the pattern of C mineralization with lag phase has not been proposed. Komilis (2006) proposed a first order degradation in series model, which included only growth phase and stationary phase. The external degradation in the first step was assumed to comprise readily, moderately, and slowly hydrolysable solid carbon. The internal cell degradation was also assumed as the mineralization from intermediate solid carbon to carbon dioxide. Change in the property of the organic material, especially plastics during the cause of degradation, was investigated using Scanning Electron Microscope (SEM) for surface morphology (Shah *et al.,* 1995).

There are two objectives in the research work. The first objective was to assess environmental impact of (1) trays made from PLA and PS and (2) garbage bag made from Polyetylene/starch 70:30 blend (PE/starch), PE/Total Degradable Plastic Additive (PE/TDPA) conventional PE garbage bag. The life cycle assessment (LCA) technique was used with the scope of study including raw materials extraction, material preparation, manufacturing, transportation, using, and waste management. The second objective was to propose a first order kinetic in series model, which included lag phase, growth phase and stationary phase. The solid carbon fractions and intermediate solid carbon fraction of plastics under aerobic composting conditions were calculated. Microcrystalline cellulose (MCE) and PE was used as positive and negative reference control. The corresponding solid hydrolysis rate constants and mineralization rate constants were also determined. The solution had been solved by non-linear regression analysis. The SEM morphology was then used to confirm the results from biodegradability testing.

OBJECTIVES

1. To collect life cycle inventory data and assess life cycle energy consumption and environmental impacts of two types of packages: firstly, two types of trays made from PLA and PS; secondly, three types of garbage bags made from PE/starch, PE/TDPA, and conventional PE.

2. To propose a kinetic model including lag phase, growth phase and stationary phase.

3. To determine solid carbon fractions, intermediate solid carbon fraction, and the corresponding solid hydrolysis rate constants and mineralization rate constants of degradable plastics under aerobic composting conditions.

Scopes

1. Life cycle inventory data include both degradable plastic trays and garbage bags packages.

2. System boundary of the study for life cycle of packages covered raw materials extraction, material preparation, manufacturing, transportation, use, and end of life management.

3. The environmental impact assessment used CML 2 Baseline 2000 method with Microsoft Excel and SimaPro 7.02 software with and the kinetic model curve fitting used Microsoft Excel Solver.

4. The functional unit (FU) is 420 liters of 20 x 14 x 1.5 cm. trays of PLA and PS, each tray weight 15.10 and 4.03 grams per tray, respectively. While, the function unit is 500,000 liter of 58.4 x 95.25 cm^2. garbage bags of PE/starch, PE/TDPA and PE, three garbage bags weight of 416.83, 93.17 and 60.83 kilogram, respectively.

5. The aerobic biodegradation under controlled composting conditions was set according to ISO 14855-99.

6. The SEM morphology was used to confirm the results from biodegradability testing.

Expected Benefits

1. Life cycle inventory data obtained from this study can be incorporated into the National Life Cycle Inventory data of basis materials and energy.

2. The research results will be useful to promote biodegradable plastics.

3. Kinetic models can be used for predicting retention time and for design and facilities of aerobic biodegradation of the biodegradable plastics.

LITERATURE REVIEW

1. History of plastics

The word plastic comes from the Greek word " plastikos " , which means 'able to be molded into different shapes' (Joel, 1995). Plastics are made long chain polymeric molecules (Scott, 1999). More than half a century ago, synthetic polymers started to substitute natural materials in almost every area and nowadays plastics have become an indispensable part of our life. Therefore, this group of materials is now considered as a synonym for materials being resistant to many environmental influences.

2. Synthetic or petroleum-based plastics

The most widely used plastics are made from inorganic and organic raw materials, such as carbon, hydrogen, and oxygen, etc. The basic materials used for making plastics are extracted from oil, coal and natural gas (Seymour, 1989).

Plastics are resistant against microbial attack, since during their short time of presence in nature evolution could not design new enzyme structures capable of degrading synthetic polymers (Mueller, 2006). Recently, petroleum-based synthetic polymers are produced worldwide to the extent of approximately 200 million tons per year and the amounts of polymers are introduced in the ecosystem as industrial waste products (Shimao, 2001).

Synthetic plastics are mostly used in packaging of products like food, pharmaceuticals, cosmetics, detergents and chemicals. Approximately 30% of the plastics are used worldwide for packaging applications. This utilization is still expanding at a high rate of 12% per annum (Sabir, 2004). They have replaced paper and other cellulose -based products for packaging because of their better physical and chemical properties, such as their strength, lightness, resistance to water and most water-borne microorganisms. The most widely used plastics used in packaging are polyethylene (LDPE, HDPE, and LLDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), etc. However, they will accumulate in the environment after the end of life.

Some synthetic plastics like polyester polyurethane, polyethylene with starch blend, are biodegradable, although most commodity plastics used now are either non-biodegradable or even take decades to degrade.

In response to this concern, an interest in environmentally degradable plastics has increased. This has raised growing concern about degradable polymers and promoted research activity world wide to either modify current products to promote degradability or to develop new alternatives that are degradable by any or all of the following mechanisms: biodegradation, environmental erosion and thermal degradation (Kawai, 1995). In the past 10 years, several biodegradable plastics have been introduced into the market.

3. Degradable or biodegradable plastics

In 1980, scientists started to look if plastics could be designed to become susceptible to microbial attack, making them degradable in a microbial active environment. Biodegradable plastics opened the way for new considerations of waste management strategies since these materials are designed to degrade under environmental conditions or in municipal and industrial biological waste treatment facilities (Witt *et al.,* 1997).

3.1 Classification under degradable mechanism

Degradation is defined as a physical or chemical change in polymer as a result of environmental factors, such as light, heat, moisture, chemical conditions or biological activity (Hamid, 2000) and (Mohee *et al.,* 2008).

Biodegradable is defined as a change in polymer facilitied by living organisms, usually microorganism (Hamid, 2000) and (Mohee *et al.,* 2008). Degradation and biodegradation process are shown in Figure 1.

3.2 Degradation pathway and composition

There are five different degradable plastics, as shown in Table 1. This table classified plastics according to both degradation pathway and composition (James and Grant, 2005).

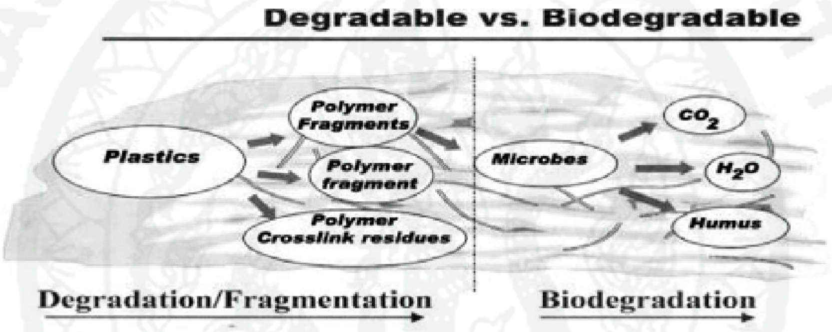


Figure 1 Degradation and biodegradation process.

Source: Mohee *et al.* (2008).

Table 1 Type of degradable polymers.

Polymer category, Degradation pathway	Composition	From renewable or non-renewable resources
Biodegradable Starch-based polymers	Thermoplastic starch derived from corn, potato or wheat, blend with additive (e.g. plasticizers)	Mostly renewable
	Thermoplastic starch derived from corn, potato or wheat, blended with polyester (PLA or PCL)	Starch component renewable, but hydrocarbon-based plastics and energy for agriculture are no-renewable
	Thermoplastic starch derived from tapioca, corn, potato or wheat, blended with polyethylene	As above
	Thermoplastic starch derived from corn, blended with PVOH	As above
Biodegradable polyesters	Polybutylene succinate (PBS)	Non-renewable
	Poly (butylenes succinate-co-adipate) (PBSA) copolymer	Non-renewable
	Polybutyrate adipate terephthalate (PBAT)	Non-renewable
	Adipic acid aliphatic/aromatic copolyesters (AAC)	Non-renewable
	Polylactic acid (PLA)	Renewable

Table 1 (Continued)

Polymer category, Degradation pathway	Composition	From renewable or non-renewable resources
Biodegradable polyesters	Polycaprolactonr (PCL)	Non-renewable
	Polyhydroxy-butyrate-valerate (PHB/V)	Renewable
	Blends of PHB with PCL	Combination renewable and non-renewable
	Modified PET	Non-renewable
Controlled degradation Masterbatch additive	Polyethylene with a thermal and/or UV prodegradant additive	Non-renewable
Water soluble polymers	Polyvinyl alcohol (PVOH) and ethylene vinyl alcohol (EVOH)	Starch component renewable, but hydrocarbon-based plastics and energy for agriculture are no-renewable
Photodegradable polymer	Thermoplastic synthetic polymer or copolymers	As above

Source: Nolan – ITU (2004)

4. Degradable or biodegradable plastics

The properties of degradable or biodegradable plastics in this study are described as follows:

4.1 Polyethylene (PE)

Polyethylene (PE) is one of synthetic polymers of high hydrophobic level and high molecular weight. It is obtained from polymerization of ethylene. The chemical structure of polyethylene is shown in Figure 2. The characteristic of PE which lead to its widespread uses are low cost, easy to process, excellent moisture barrier properties, and good resistance. However, the characteristic structure makes PE non-susceptible to degradation by microorganism.

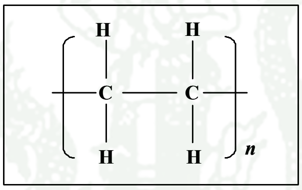


Figure 2 The chemical structure of PE.

Source: Shah *et al.* (2008)

Classification of PE

Polyethylene is classified into several different categories based mostly on its mechanical properties. Significant differences in mechanical properties are observed in low density polyethylene (LDPE), linear low density polyethylene (LLDPE) and high density polyethylene (HDPE).

Structural parameters, such as density or crystal structure, molecular weight and its distribution, short chain branching, long chain branching length and amount and crystalline morphology are the key factors that control the properties.

HDPE is the most crystalline PE, since its chains are linear and contain very little branching. It shows high modulus, medium tensile properties, poor impact and tear resistance (Shang, 2004).

LDPE contains long chain branching in the order of 1–3 per 1000 carbon atoms as well as 10–30 short chain branching per 1,000 carbon atoms. It shows low tensile strength and modulus, medium impact and tear resistance.

LLDPE has a wide range of short chain branching, depending on the type of catalyst and comonomers (butene, hexene or octene) of ethylene. It generally has good tensile, impact and tear resistance, the type and amounts of short chain branching have a significant effect on the physical properties.

For waste management, a comprehensive study of PE biodegradation has shown that some microorganism could utilize PE with low molecular weight (Yamada-Onodera *et al.,* 2001). Therefore, the biodegradation always follows photodegradation and chemical degradation. Biodegradation of polyethylene is known to occur by two mechanisms: hydro-biodegradation and oxo-biodegradation (Bonhomme *et al.,* 2003). These two mechanisms agree with the modification due to the two additive, starch and pro-oxidant, use in the synthesis of biodegradable polyethylene.

4.2 Starch-polyethylene (PE) blends

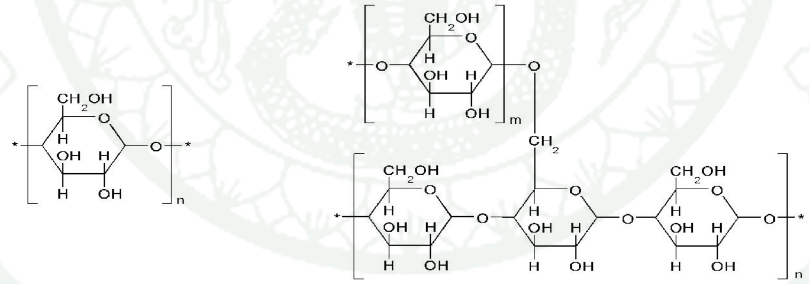
The starch component of these polymers will degrade due to the action of microorganisms such as bacteria, fungi, algae and starch digesting enzyme (amylase). But, degradation behavior will depend on the amount of starch included in the blend. In high starch formulations, the starch domains are connected to allow complete degradation of starch. It is expected only at high levels of starch additive, around 30 % by weight of starch in the blend (Papet *et al.,* 1989). In recent years, some products currently on the Australian market are labeled “total degradable”, which contain around 30% starch to 70% polyethylene (Nolan – ITU, 2004).

1.2.1 Starch

Starch is built up from chains of glucose ($C_6H_{12}O$). The two major components in starch are mylose (long, unbranched chains) and amylopectin (long, cross-linked chains), with different structures. (Davis, 2003). The chemical structure of mylose and amylopectin are shown in Figure 3.

Starch is a polysaccharide (carbohydrate) found in all green plants and is synthesized in the organs of plants as a food reserve for periods of dormancy, germination and growth. Due to these functions, starch can be easily biodegraded through enzyme activity (Davis, 2003).

Starch exhibits hydrophilic properties and consists of strong hydrogen bonds and it is for these reasons that starches are unsuitable for thermoplastic applications as degradation sets in before thermal melting (Davis, 2003) and (Kiratisaevee, 2000).



(a) Amylose (b) Amylopectin

Figure 3 The chemical structure of starch. a) Amylose b) Amylopectin.

Source: Crop and Food Research (2004)

4.3 Polyethylene with total degradable additive

Environmental Product Inc. (EPI) has developed Totally Degradation Plastic Additive (TDPE^{TM}) formulation that, when compounded with conventional polymers at appropriate levels, control the lifetimes of plastics. Stability is maintained during processing, storage and short-term end use.

Prodegradants in the EPI degradable plastics include additive based on transition metal ions (Mn, Cu, Fe, Co, Ni) and metal complex (cobalt stearate, cerium stearate), which render conventional polyethylene susceptible to hydroperoxide oxidation. The important of these additive is that they are activated both by action of sunlight and by heat (Nolan-ITU, 2004)

4.5 Polystyrene (PS)

Polystyrene (PS) is a synthetic plastic used in the production of disposal cup, packaging materials, in laboratory were, in certain electronic uses. PS is used for its lightweight, stiffness and excellent thermal insulation. It is a versatile polymer resin sold in three main forms: general purpose polystyrene also known as crystal polystyrene (GPPS), high impact polystyrene (HIPS) and expandable polystyrene (EPS) (PlasticasEurope, 2008). The chemical structure of polystyrene is shown in Figure 4.

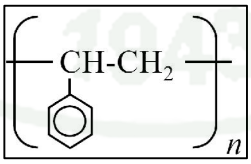


Figure 4 The chemical structure of polystyrene.

Source: Shah *et al.* (2008)

GPPS is manufactured by polymerization by polymerization of styrene alone (PlasticasEurope, 2008). GPPS is a clear, hard, and usually colorless. It is a versatile thermoplastic polymer, which softens when heat and can be processed by extrusion or various forming or molding (Dow Chemical Company, 2008).

HIPS is obtained by adding by polybutadiene rubber at the styrene polymerization. It is often specified for low strength structural application when impact resistance required.

EPS is usually white and hard foam which is mostly used as a packaging material or as shock absorbers for a wide range of applications (Tan and Khoo, 2005). It is produced from a styrene. Air makes up approximately 95-98% of overall content of the material.

HIPS and GPPS are used in many applications such as food and non-food packaging, yoghurt pot, meat trays, etc. PS is also easily foamed in order to manufacture insulation boards and lightweight foam packaging. The packaging market is the main market and accounts for around half of the European PS (PlasticasEurope, 2008) and (Dow Chemical Company, 2008).

4.6 Polylactic acid (PLA)

Polylactic acid (PLA) is linear aliphatic polyester produced by poly-condensation of naturally produced lactic acid or by the catalytic ring opening of the lactide group. Mitsui Chemical developed a new process based on direct polycondensation of L-lactic acid to enable the production of high molecular weight PLA without the use of an organic solvent. Cargill Dow uses corn for PLA production and utilizes ring-opening polymerization through the lactide intermediate.

(a) L – Lactic acid (b) D – Lactic acid

Figure 5 The structure of lactic acid. a) L- Lactic acid b) D- Lactic acid.

Source: Narayan *et al.* (2005)

Due to lactic acid is a chiral molecule. The optically active lactic acid has an "L" and "D" stereoisomer, as shown in Figure 5. Production of the cyclic lactide dimmer results in three forms: the D, D-lactide (called D-lactide), L, L-lactide (called L-Lactide) and L,D or D,L lactide (called meso lactide). PLA with high L-lactide level can be used to produce crystalline polymers while the high D-lactide level is more amorphous (Vink *et al.,* 2003). Usually, high L- lactide level is desirable intermediate for the production of PLA (Wolf, 2005).

Production

The first generation of PLA will be produced from the renewable resources like corn, sugar beets or rice. The following corn wet mill converts the starch in the corn grain into dextrose. Dextrose is converted to lactic acid utilizing fermentation and series of purification steps (low molecular weight PLA). Lactic acid is converted to cyclic dimmer, lactide, which is purified using distillation (Vink *et al.,* 2003). In the final step, high molecular weight PLA (higher 100,000 Dalton) is produced by polymerized lactide in a solvent-free ring opening polymerization and process into pellets (Wolf, 2005). Polymerization and lactide to PLA granules are shown in Figure 6.

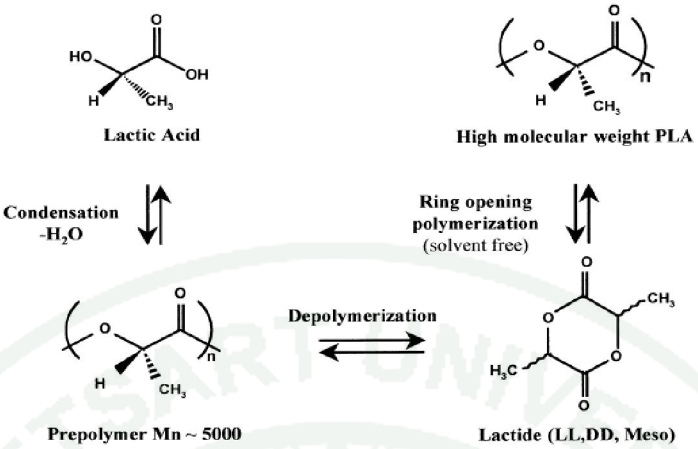


Figure 6 PLA manufacturing overview.

Source: Vink *et al.* (2003).

Cargill began researching PLA production technology in 1987, and began production of pilot plant quantities in 1992. In 1997, the first commercial PLA product was a joint venture between the U.S. companies Cargill and Dow Chemical Company, Inc., creating Cargill Dow Polymers LLC (Vink *et al.*, 2003).

The applications for PLA are thermoformed products such as drink cups, take-away food trays, containers and planter boxes. The material has good rigidity characteristics, allowing it to replace PS and polyethylene terephthalate (PET) in some applications. Presently, PLA, one of biodegradable plastics, has high economic potential for consumer applications e.g. agricultural plastics, diapers, and electric appliances, approximately 70% of PLA for packaging application (Dornburg *et al.,* 2006).

5. Life Cycle Assessment (LCA)

5.1 Definition of Life Cycle Assessment

LCA is an environmental auditing tool that quantifies the environmental burdens of a specific process inclusive of all its related systems. All direct and indirect environmental impacts associated with the product, process or activities are included in the assessment as the concept of "cradle to grave" (SETAC, 1993).

LCA can be regarded as a decision support system. One may think of decisions on the purchase of products, on policy measures like "eco-labeling", on "green marketing" or on the (re)design of products as being based on the information of an LCA. These decisions are outside the scope of an analytical tool such as LCA. However, the methodological aspects, notably concerning the identification on options for improvement, are part of an LCA.

The purpose of LCA is to compile and evaluate the environmental consequences of different options for fulfilling a certain function. This cradle-to-grave analysis involves a holistic approach, bringing the environmental impacts into one consistent framework, wherever and whenever these impacts occurred or will occur. The final consumption of products happens to be the driving force of economy and environment. Therefore, this final consumption offers core opportunities for indirect environmental management along the whole chain or network of unit processes related to a product (Varabuntoonvit, 2008).

A fundamental reason for choosing such an approach is that a LCA avoids 'problem shifting'. It is important in eco-design not to solve one environmental problem merely by shifting it to another stage in product's life cycle. For example by making a car from aluminum instead of steel, the gasoline consumption of the car is reduced, but the production of aluminum requires more energy than that of steel. Only when all of these facts are taken into account, one can judge whether a car made from aluminum is truly more environmentally friendly than one made of steel.

LCA can play a useful role in both public and private product policy. This may involve an environmental comparison between existing products, as well as the development of new products. A major application involves green procurement, which is a ‘green’ purchasing policy which can be performed by both authorities and companies. For instance, LCA is used in the design of new cars in Sweden (Volvo) and in the German automotive industry (Daimler Benz). The way of performing LCA depends upon the intended use of results, as shown in Table 2 (Varabuntoonvit, 2008). The main purposes of LCA are:

- The analysis of the origins of the problems related to a particular product
- The comparison of improvement variants of a given product
- The design of new products
- The choice between a number of existing comparable products

Another purpose is concerned with eco-labeling (i.e. assigning a ‘green label’ to environmentally friendly product alternatives), enabling consumers to make comparisons between products. Eco-labeling programs are increasing based on LCA, as for example, the eco-labeling program of the EU (the Blue Angle eco-labeling program in Germany, the Green swan eco-label in Scandinavia, etc.). According to the ‘greening’ of the construction industry in the Netherlands, the new houses must fulfill minimum certain environmental requirements. These include requirements on the environmental burdens of all materials used in the building of a house, based upon quantitative LCA.

Table 2 The way of performing LCA and intended use.

Intended use	The way of performing
Exploration of options	The LCA study is performed to get a first impression of the environmental effect of certain options.
Company internal innovation	The LCA study is performed to assess the environmental impact of company internal product improvements, product development or technical innovations.
Sector wide innovation	Similar to above, only sector wide (in a formal organization representing a branch of chain companies it can be considered as an internal activity).
Strategy determination	The LCA study is performed to assess the environmental impact of strategic scenarios.
Comparison	The LCA study is performed to assess if a product or system meets certain environmental standards or if it is environmentally sounder than another product or system.
Comparative assertion disclosed to the public	The LCA study is performed for public justification of the environmental aspect of a decision made with respect to a product or system.

Source: Varabuntoonvit (2008)

5.2 Methodology of life cycle assessment

The complexity of LCA requires a fixed protocol according to which an LCA study should be performed. Such a protocol has been established by ISO and it is generally referred to as procedural framework. Figure 7 shows the framework in ISO 14040 (2006) which distinguishes four phases of life cycle assessment (LCA) as below:

Goal definition and scoping

- Inventory analysis

- Impact assessment
- Interpretation

In the goal definition and scoping, the purpose of study and its scope are defined in relation to how the results are to be used. The functional unit is established in this step, with the necessary data and information needed for the inventory and impact assessment also identified. The selection of functional unit is straightforward for processes (usually 1 ton of product), but more debatable for products where product effectiveness rather than mass or volume becomes of key importance. For example, "kilo watts hours of electricity" used as the functional unit of electricity generating system of different power plant can be compared.

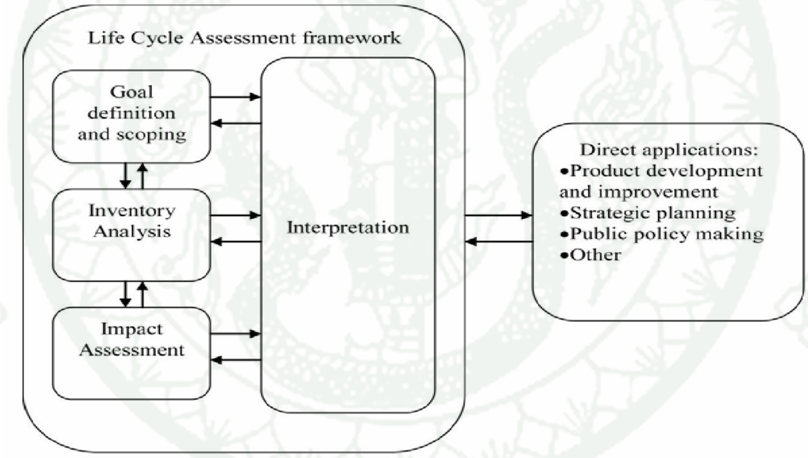


Figure 7 Procedural framework of LCA.

Source: ISO 14040 (2006)

The next component of LCA is inventory analysis, which quantifies the inputs (using mass and energy balances) and output (products and releases to air, water and land) for all processing steps included in the system boundary. The life cycle of each of products considered is defined by assembling the processes which constitute the different phases of the life cycle. These phases consist of industrial processes such as the production of materials or components, consumer processes such as the use and maintenance of products, and post-consumer processes such as waste handling and recycling. The collection of combined processes with their mutual relationship is called a process tree. The inventory also comprises the collection of the processes data. Process data consist of economic data (use and production of material, products and services) and of environmental data (extractions of resources and emissions of substances). The result of the inventory is a list of the loading onto the environment in term of extraction and emissions caused by a functional unit of the product analyzed.

The impact assessment component of an LCA is defined as a quantitative and/or qualitative process to identify, characterize and assess the potential impacts of the environmental interventions identified in the inventory analysis. According to the SETAC 'Code of Practice', impact assessment consists of three distinct steps: classification, characterization (including normalization), and valuation.

- Classification step, the resources used and wastes generated are grouped into impact categories based on anticipated effects on the environment. These impact categories might include environmental problems such as resource depletion, global warming, acidification and photochemical oxidant formation.

- Characterization step, which take into account both the magnitude and potency of the inventory categories. The potential contribution to each environmental impact category is quantified. Normalization is an optional step and is carried out in order to normalize the data from the characterization step in relation to the actual magnitude of the impacts in some given area, making it easier to understand the relative magnitude of each environmental impact score.

- Valuation step, directly follows the classification and characterization steps, with this stage being a subjective analysis of how the different environmental problems should be weighted against each other. These weighting factors may be established in a panel, either on the national, regional or global level, with the general idea being to directly investigate the preferences of society for reduction of environmental impacts.

There are other methods available for conduction the impact assessment and in comparison to the approach taken by SETAC, some of these methods either weight the inventory data directly or are partly based on characterization data. Some methods are based on monetary values, or society’s willingness to pay to avoid impacts on certain ‘safeguard subjects’. The Environmental Priority Strategies (EPS) is an example of weighting factor being directly applied to the inventory data to form and environmental profile of the system. The impact assessment may also be based on political or ecological goals or standards, often referred to as distance-to-target approaches. More recent weighting systems based on ecological critical levels, such as the Eco Indicator method, have also been developed.

The improvement assessment is in interpretation is the only component which does not yield a description of the interactions between life cycle and environment; it gives information on the opportunities to decrease the environmental burdens associated with a functional unit of product. Improvement assessment involves looking at how the results of an LCA can be used, not only in terms of how the adverse environmental impacts of the system can be reduced, but how the results should be interpreted in corporate with other considerations such as cost (Varabuntoonvit, 2008).

6. Environmental impact of degradable plastics

There are a number of many literatures have been reported environmental assessment of petroleum-based and biodegradable plastic which derived from renewable resources. It can be observed that the energy used and GHG emissions of biodegradable plastics are saving from aliphatic polymer e.g. PE, PS and PET. The alternative waste treatment, composting and landfill or incineration with energy recovery obtained energy and environmental impact reduction. Details of each literature are given as paragraphs below.

In a cradle-to-gate, Petal *et al.* (1999); Vink *et al.* (2003) and Bastioli (2005) reported that petroleum-based plastics contribute the energy consumption and GHG emissions are higher than that for biodegradable plastics. However, for eutrophication, PE tends to score better Bastioli (2005). The synthetic polymer bag derived from petroleum petroleum which have higher impacts on resource impacts (abiotic depletion) (James and Grant, 2005; Wolfensberger and Dinkel, 1999). For starch polymer pellets, it was found that energy requirements and GHG emissions are mostly 35%-70% and 30%-80% respectively lower than that for PE (Bastioli, 2005). For PLA pellets, it was found that energy requirements for PLA are 30%-40% below those for PE, while GHG emissions are about 25% lower (Vink *et al.,* 2003). Process improvement for bioplastics production become more attractive because of its several benefits such as wind power replaced grid electricity, whole part of crops derived the biomass feedstock, bio-refinery integrated process (Vink *et al.,* 2003), and triple-effect evaporation (Paoluglam, 2005) are used for bioplastics production. For example, on cradle-to-gate basis, the gross energy to produce PP container is higher than PLA container 1.65 times due to advantage of triple-effect evaporation (Bohlman, 2004).

In cradle-to-gate factory (package), it was found that the higher weight of the containers resulted in high environmental impacts. Tan and Khoo (2005) found that the re-design EPS inserts has lower environmental impacts than all of the CPB. The environmental benefits of the re-design EPS was due to it consume fewer raw materials. Madival *et al*. (2009) found that PET contributed the highest in almost all the impact categories due to the higher weight of the containers (PLA and PS).

In cradle-to-grave, the life cycle assessment (LCA) that examined whether a re-use and recycle strategy for a plastic-based packaging that substantially reduces the quantity of waste to landfill would also reduce the overall environmental burden Ross and Evans (2003). James and Grant (2005) found that reusable bags have lower environmental impacts than all of the single-use bags. Molgaad (1995) studied a comparison of environmental impacts and resource consumption of various disposals of plastics. It was found that the recycling of plastics from municipal solid is environmentally and resource sounds because it can produce a recycled plastic, which have properties comparable to virgin plastics (Molgaad, 1995; Arena *et al.,* 2003).

Moreover, Roy *et al*. (2009) reported that the alternative waste management scenarios are useful. An integrated waste management system would be much better to reduce overall environmental burdens of plastics waste. Incineration with heat recovery is also suitable with management (Molgaad, 1995; Suwanmanee *et al.,* 2010). Landfill with energy recovery from methane collection also shows a good result as it contributes GHG reduction and energy product (Bohlman, 2004). The GHG emissions obtained from the electricity generated using fossil fuels can be replaced those obtained from the electricity generation from the landfill with energy recovery from methane collection (Bohlman, 2004; Suwanmanee *et al.,* 2010). Wolfensberger and Dinkel (1999); Munoz *et al.* (2004); Jame and Grant (2005) and Razza *et al.* (2009) reported that composting is suitable for biodegradable solid waste due to the use of compost contributes to soil amelioration and it replaces synthetic fertilizers to some extent. Moreover, if the degradable material can be kept out of landfill, and manage through composting the greenhouse gas (GHG) emissions will be reduced due to it not eliminated. Munoz *et al.* (2004) reported that composting of biodegradable solid waste is the best way to improve environmental factors.

In the case of landfilling, some studies account for methane (CH_4) emissions because of anaerobic emissions while others do not take this into consideration. This can have a considerable impact on the results due to the relatively strong greenhouse gas effect of CH_4. As a consequence the overall global warming potential (GWP) of biodegradable polymers manufactured from renewable raw materials may be higher than for petrochemical plastics depending on the waste management system chosen for the latter (Bohlman, 2004; Bastioli, 2005; Suwanmanee *et al.,* 2010).

In the case of incineration, various polymers were disposed by incineration after their useful life. It was found that the energy used and carbon dioxide emission of starch polymer was saving from conventional LDPE, which were 28-55 GJ/ton polymers and 1.4-3.9 ton CO_2/ton polymers. Moreover, energy used and carbon dioxide emissions of LDPE, and starch/petrochemical products blend were higher than starch polymer (Petal *et al.*, 1999; Bastioli 2005).

7. Kinetic composting of biodegradable and degradable plastics

Recently, many literatures have been studied composting kinetic that describes the decomposition of organic waste. The parameters obtained from the model analysis that is useful to estimate the C mineralization of several organic materials (Komilis, 2006). Degradation curve of the carbon dioxide production from composting consists of three stages including lag phase, growth phase, and stationary phase (Hamid, 2000). The several models studied under control composting conditions are first order kinetic models.

Many literatures have reported kinetic models of decomposition of plastics or organic waste into carbon (C) mineralization. They are proposed in order to either describe phenomenon or determine corresponding kinetic parameters. The theory and details of C mineralization of each model are given as follows:

7.1 Zero order kinetic model

The first model referred herein as zero-order (Seyfried and Rao, 1998) the equation can be written as

$$C_t = \mathrm{k_s t} + \text{intercept} \tag{1}$$

where, C_t is percentage of cumulative CO_2-C mineralized at the time t (day), k_s is zero order rate constant (day^{-1}) and intercept represents a pool of highly mineralizable C.

7.2 First order kinetic model

The second model is first-order exponential equation (Murwira, 1990), the equation can be written as

$$\mathrm{C_t = C_0 \cdot (1 - e^{kt})} \tag{2}$$

where, C_t is percentage of cumulative CO_2-C mineralized at the time t (day), C_0 is the percentage of potentially mineralizable C, k is mineralization rate constant (day^{-1}).

7.3 First-first order kinetic model

The carbon mineralization of organic wastes follows a combined two-step kinetic: one that decomposes faster during a few weeks of incubation and the other that decomposes more slowly during the process (Molina *et al.*, 1980). Therefore, the first-first order kinetic model is shown as the following equation

$$C_t = C_r \cdot (1 - e^{k_r t}) + C_s(1 - e^{k_s t}) \tag{3}$$

where, C_t is percentage of cumulative CO_2-C mineralized at the time t, C_r, C_s are percentages of rapidly and slowly mineralizable fractions, and k_r and k_s are the rapid and slow reaction rate constants (day^{-1}), respectively. The sum of C_r and C_s has the same physical meaning as C_0 in its first-order exponential equation model.

Another variation of first-order model is the first-order E model (Jones, 1984):

$$C_t = C_0 \cdot (1 - e^{k_r t}) + C_n \tag{4}$$

where, the C_n is the additional parameter (percentage of C mineralizable fraction) that defines a separate pool of easily decomposition, C_0 are percentage of active C fraction, and k_s is reaction rate constant of the active C fraction (day^{-1}).

Finally, the special model is an approximation of double exponential model for which duration is short in comparison with the half-life of the resistant pool (Bond and Rosswall, 1987):

$$\mathrm{C_t = C_r \cdot (1 - e^{k_r t}) + k_s t} \tag{5}$$

where, C_t is percentage of cumulative CO$_2$-C mineralized at time t, C_0 is the percentage of potentially mineralizable C, k_r is mineralization rate constant (day^{-1}), and $k_s t$ is the large resistant C pool that mineralizes at low and constant rate.

7.4 First-zero order kinetic model

The carbon mineralization of organic wastes follows a combined two-step kinetic: one first order, rapid phase, and the other, zero order, slow phase (Bernal *et al.,* 1998). Therefore, the first-zero order kinetic model can be rewritten by the following equation

$$\mathrm{C_t = C_r \cdot (1 - e^{k_r t})} + C_s \mathrm{k_s t} \tag{6}$$

where, C_t is percentage of cumulative CO$_2$-C mineralized at the time t, C_r, C_s are percentage of rapidly and slowly mineralizable fractions, and k_r and k_s are the rapid and slow reaction rate constant (day^{-1}), respectively.

7.5 Levi-Minzi kinetic model

Levi-Minzi model was used by Levi-Minzi *et al.* (1990) to express net mineralization with exponential kinetic. This kinetic model is expressed as

$$C = kt^{m} \tag{7}$$

where, C is the net cumulative CO_2-C mineralized (mg/kg) at time t, k is characterizes the units used for the variable (mg/kg day) and m is the shape of curve.

7.6 First-order reaction in series kinetic model

Mathematical model of a pseudo-homogeneous model in a batch reactor process can be initiated from its general mass balance form as follows (Levenspiel, 1999):

$$\mathbf{A} \xrightarrow{\mathbf{k_1}} \mathbf{R} \xrightarrow{\mathbf{k_2}} \mathbf{T}$$

rate equation for the three components can be rewritten by the following equation

$$r_A = \frac{dC_A}{dt} = -k_1 \cdot C_A \tag{8}$$

$$r_R = \frac{dC_R}{dt} = \left(k_1 \cdot C_A - k_2 \cdot C_R\right) \tag{9}$$

$$r_T = \frac{dC_T}{dt} = k_2 \cdot C_R \tag{10}$$

therefore the rate equation of first-order reaction in series model are

$$C_A = C_{A0} \cdot e^{-k_1 \cdot t} \tag{11}$$

$$C_R = k_1 C_{A0} \cdot \left(\frac{e^{-k_1 \cdot t}}{k_2 - k_1} + \frac{e^{-k_2 \cdot t}}{k_1 - k_2} \right) \tag{12}$$

$$C_T = C_{A0} \cdot \left(1 + \frac{k_2 e^{-k_1 \cdot t}}{k_2 - k_1} + \frac{k_1 e^{-k_2 \cdot t}}{k_1 - k_2} \right) \tag{13}$$

where, C_T is percentage of cumulative C-CO_2 production at time t; C_A and C_R percentages of initial and intermediate hydrolysable solid carbon fractions at time t, C_{A0} is percentage of total initial solid carbon; k_1 and k_2 are reaction rate constant (day^{-1}).

Several literatures applied the mentioned above models to investigate the decomposition of plastics or organic waste into mineralization C. The first order model of the hydrolysable of organic polymer to soluble organic matter has been studied by Hamelers (1996). Bernal *et al.* (1998) have studied the organic C mineralization rates of different organic waste and emphasized C mineralization which combined first-and zero-order kinetic model. Hamoda *et al.* (1998) and Huang *et al*. (2000) have studied the first order model to fit organic carbon from the composting kinetics. Komilis (2006) has studied the first order in series mathematical model which was developed to calculate the different solid carbon fractions that hydrolyze at different rates to water soluble carbon, for six biodegradable solid waste components under aerobic conditions. Hydrolysis rate constants incorporate three first-order function, describing the degradation of readily, moderately and slowly hydrolysable solid carbon fraction. The kinetic study of the readily hydrolysable carbon fraction has hydrolysis rate constants higher than 0.06 day^{-1}. The value of moderately hydrolysable rate is less than 0.06 day^{-1}. The slowly hydrolysable rate was set to zero. The first order mineralization rates, this value is taken equal to 10^6 day^{-1}. Tosun *et al.* (2008) have studied the kinetic rates of rose processing waste and mixed organic fraction of municipal solid. The experimental data has been analyzed by kinetic model, the best fitting including the first-zero-order and first-first-order kinetic model. A decomposition rate model considered the rapid and slow biodegradable carbon fraction. Mason (2008) has studied the kinetic model, including a single exponential model, a double exponential model and a non-logarithmic Gompertz model for examining the patterns of 32 constant temperature substrate degradation process obtained from the composting literature. The lag phase was not predicted the model both single and double exponential function. Using either a single exponential model or a double exponential model provided a good fit on the post-lag phase data.

MATERIALS AND METHODS

Materials

1. Computer and software

1.1 Personal computer (Intel core 2 Duo processor)
1.2 Microsoft Windows software with Microsoft Office 2003
1.3 SimaPro software version 7.02

2. Equipment

2.1 Digital balance, 4 digits (Denver Instrument)
2.2 Vacumn oven chember (Cole pamer)
2.3 Beaker
2.5 pH meter
2.6 Oven
2.7 Tractor
2.8 Digital thermometer
2.9 Sieve 2 mm., 5 mm.
2.10 Plate
2.11 Nipper
2.12 Polyethylene frame
2.13 Vacumn pump

3. Material and chemical

3.1 Deionized water
3.2 Distilled water
3.3 Agricultural waste

4. Equipments for Sample analysis

3.1 Scanning electron microscope (SEM; SEM-JSM 6301F model)
3.2 Tensile strength (Universal Testing Machine, Instron Model 55R4502)
3.3 Thickness (Digimatic micrometer, Mitutoyo)
3.4 Element anaysis (% C H N)
3.5 Gas analyser
3.6 Digital camera (Nikon)

Methods

This part was divided into two parts – the first step, data collection from experiment and secondary source, and the second step, data analysis for environmental impact and biodegradable kinetic of plastics.

1. Goal of the study

The goal of this research was to assess life cycle energy consumption and environmental impacts of two types of packages and calculate solid carbon fractions, intermediate solid carbon fraction, and the corresponding rate constants of degradable plastics under aerobic composting conditions.

2. Scope and system boundary

2.1 Functional unit of LCA study

In this research, the functional was divided into two parts. The first part, the functional unit (FU) is 420 liters of 20 x 14 x 1.5 cm. trays of PLA and PS, two trays weights of 15.10 and 4.03 grams per tray, respectively. The second part, the function unit is 500,000 liter of 58.4 x 95.25 cm. garbage bags of PE/starch, PE/TDPA and PE, three garbage bags weight of 416.83, 93.17 and 60.83 kilograms, respectively. The properties of three types of garbage bags are shown in Table 3.

The sample of PLA and PS trays and garbage bags were shown in Figure 8 and Figure 9, respectively.

Table 3 The properties of PE/starch, PE/TDPA, and PE garbage bags.

Properties	PE/starch	PE/TDPA	PE
Thickness (mm.)	2.32E-01	1.80E-04	1.8E-04
Tensile (N/mm^2)	17.87	27.7	29.15

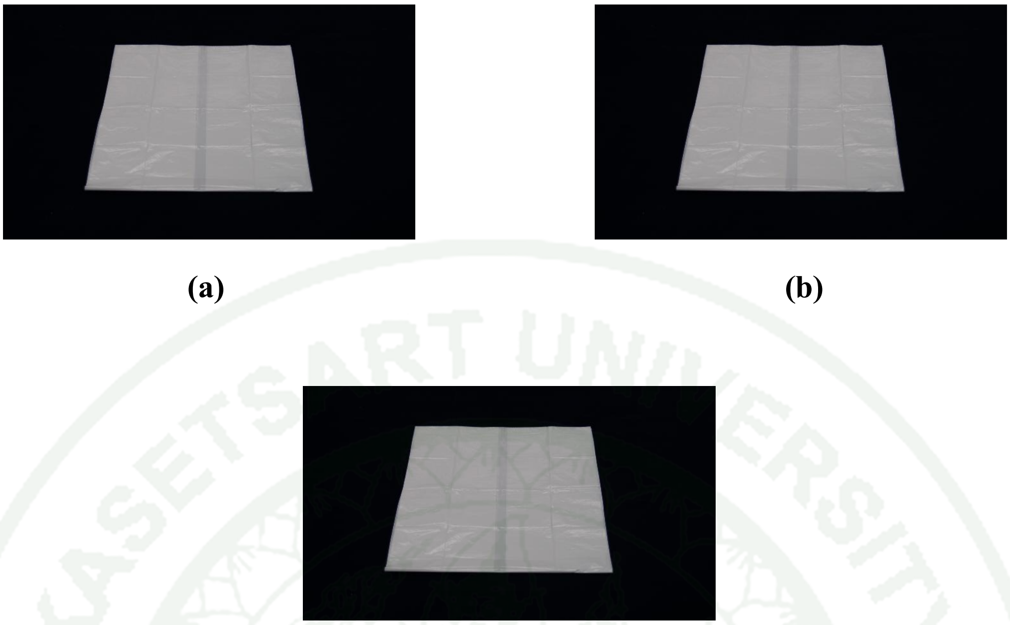
2.2 System boundary

The purpose of this study was to assess environmental impact throughout the life cycle of two types of tray, namely PLA and PS trays and three types of garbage bags, namely PE/starch, PE/TDPA and PE. Six phases along the life cycle of trays and garbage bags: raw materials extraction, materials preparation, manufacturing, using, transportation, and waste management were considered.

The system boundary of trays and garbage bags were shown in Figure 10 and Figure 11, respectively.


(a) (b)

Figure 8 Tray samples. a) PLA b) PS.



(a) (b)

(c)

Figure 9 Garbage bag samples. a) PE/starch b) PE/TDPA c) PE.

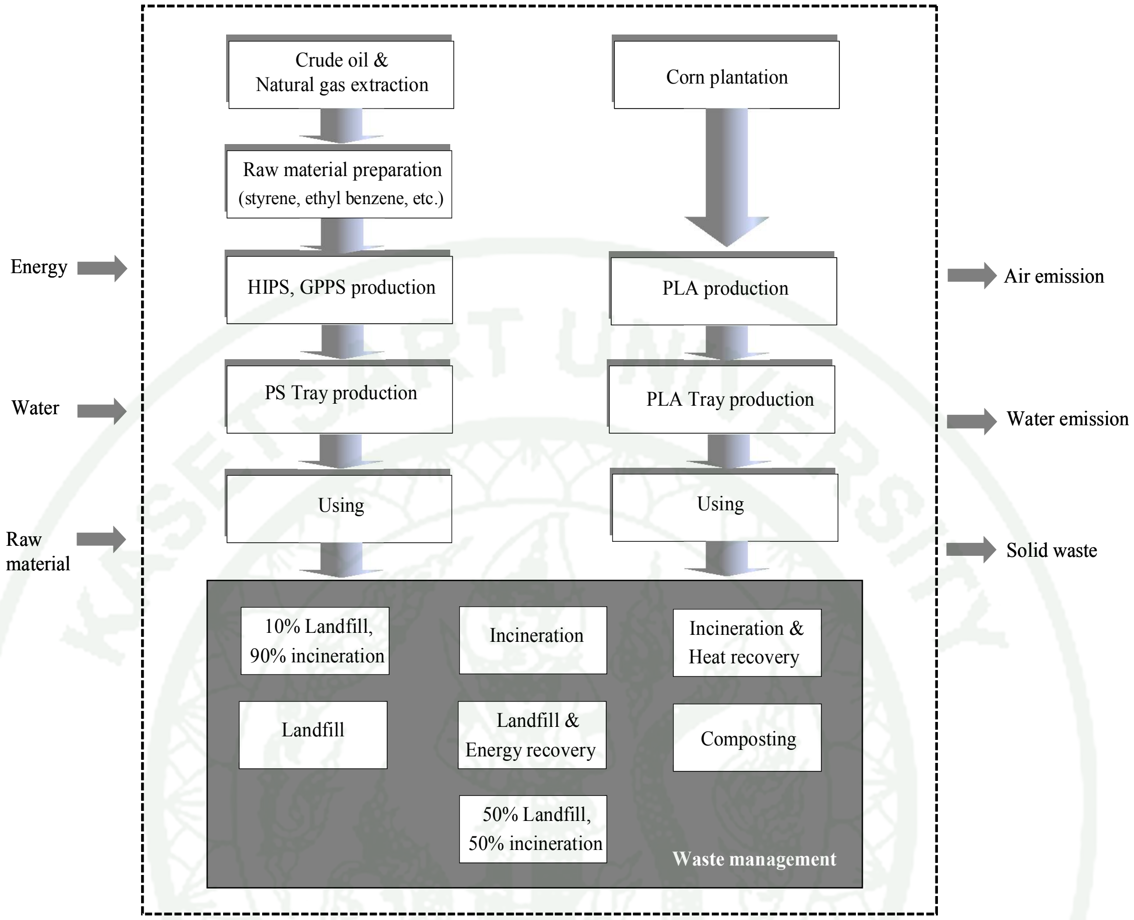


Figure 10 System boundary of PLA and PS trays with end of life management.

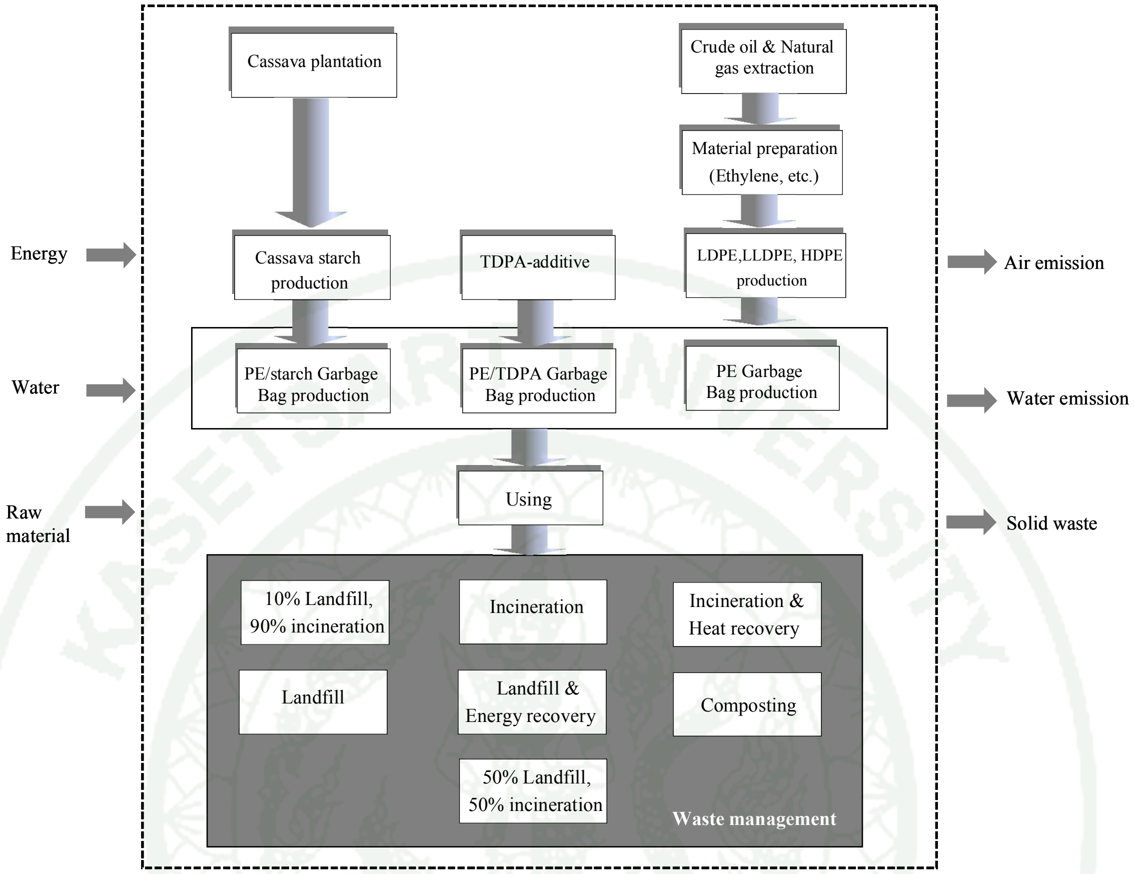


Figure 11 System boundary of four types of garbage bag packages including PE/starch, PE/TDPA and PE with end of life management.

2.3 Assumptions

2.3.1 The investigation based on Electricity Generating Authority of Thailand data in 2009. Fuels used to generate electricity for fuel fired power plant in Thailand including: natural gas, oil, and coal.

2.3.2 Natural gas, heavy oil, and coal were supplemented from secondary source in Thailand during 2008 (Varabuntoonvit, 2008).

2.3.3 Tap water and all chemicals e.g. ammonium sulphate, phosphorus, potassium chloride, etc. data was available from SimaPro 7.02 (Pre Consultants, the Netherland).

2.3.4 For life cycle of PLA tray derived from corn, the CO_2 absorption was calculated from corn growing (CCAN, 2009).

2.3.5 For life cycle of PE/starch garbage bags, CO_2 absorption during cassava growing and emission combustion of starch were not considered.

3. Life Cycle Inventory (LCI) data

3.1 LCI data of tray package

3.1.1 LCI data of PLA tray

The LCI analysis was carried out by collecting the necessary information from a variety of sources, i.e., on-site interviews, domestic research reports, journals and government publications. Detailed data source of this stage is shown in Table 4.

3.1.2 LCI data of PS tray

Crude oil and natural gas extraction were available from SimaPro 7.02 (Pre Consultants, the Netherland). The LCI data on the raw materials preparation phase (styrene monomer, ethyl benzene, naphtha, polybutadiene rubber and peroxide), were collected from database of SimaPro 7's LCA software. GPPS and HIPS data were supplemented from Paoluglam (2005) based on the production in 2005. For the PS trays production, the LCI data was sourced from a manufacturing of the PS trays in Thailand during 2007. The LCI data of various waste management scenarios for PS were supplemented same sources as PLA. Detailed data source of this stage is shown in Table 5.

3.2 LCI data of all garbage bags

LCI data of PE/starch, PE/TDPA, and PE garbage bag production was supplemented from national life cycle inventory database (MTEC, 2009a), which was about 50% of total capacity in Thailand. Cassava cultivation and cassava starch production data was collected from secondary source (Khongsiri, 2009). Crude oil and natural gas extraction and HDPE production were available from SimaPro 7.02 (Pre Consultants, the Netherland). These studies supplemented natural database in Thailand for ethylene, LDPE and LLDPE production data 2007 (MTEC, 2009a). Data of domestic distances supplemented from the Department of Highways. Data of international distance of crude oil and natural gas transportation to Thailand was available from Karom (2009). Distance for the whole transportation stage was based on average distance in Thailand. The LCI data of various waste management scenarios for garbage bag were supplemented same sources as PLA. Detailed data source of this stage for various garbage bags are shown in Table 6.

Table 4 Data source of PLA trays.

Step	Type data*	Data sources
corn plantation	2nd Data	- SimaPro 7.0 Database
PLA Production	2nd Data	- Vink *et al*. (2003)
		- Johansson (2005)
Tray Production	1st Data	- Polymer Chemistry Research unit
Transportation	1st Data	- Department of Highway
	2nd Data	- Paoluglam (2005)
Waste management		
- 90% Landfill, 10% incineration	1st , 2nd Data	- Experiment and Molgaard (1995)
- Incineration	1st , 2nd Data	- Experiment and Molgaard (1995)
- Incineration with heat recovery	1st , 2nd Data	- Experiment and Molgaard (1995)
- Landfill	1st Data	- Experiment
- Landfill with energy recovery	1st , 2nd Data	- Experiment and Bohlmann (2004)
- Composting	1st Data	- Experiment
- 50% Landfill, 50% incineration	1st , 2nd Data	- Experiment and Molgaard (1995)

Note: * 1st is Primary data.
2nd is Secondary data.

Table 5 Data source of PS trays.

Step	Type data*	Data source
Crude oil and natural gas extraction	2nd Data	- SimaPro 7.0 Database
GPPS and HIPS Production	2nd Data	- Paoluglam (2005)
Tray Production	1st Data	- Tray factory
Transportation	1st Data	- Department of Highway
	2nd Data	- Paoluglam (2005)
Waste management		
- 90% Landfill, 10% incineration	1st , 2nd Data	- Experiment and Molgaard (1995)
- Incineration	1st , 2nd Data	- Experiment and Molgaard (1995)
- Incineration with heat recovery	1st , 2nd Data	- Experiment and Molgaard (1995)
- Landfill	1st Data	- Experiment
- Landfill with energy recovery	1st , 2nd Data	- Experiment and Bohlmann (2004).
- Composting	1st Data	- Experiment
- 50% Landfill, 50% incineration	1st , 2nd Data	- Experiment and Molgaard (1995)

Note: * 1st is Primary data.
2nd is Secondary data.

Table 6 Data source of three garbage bags.

Step	Type data*	Data source
Crude oil and natural gas extraction	2nd Data	- SimaPro 7.02 Database
Ethylene Production	2nd Data	- National life cycle inventory database (MTEC, 2009a)
HDPE production	2nd Data	- SimaPro 7.02 Database
LDPE/LLDPE production	2nd Data	- National life cycle inventory database (MTEC, 2009a)
Cassava plantation	2nd Data	- Khongsiri (2009)
Cassava starch	2nd Data	- Khongsiri (2009)
TDPA-additive	2nd Data	- Freepatents (2005)
Garbage bag Production	2nd Data	- National life cycle inventory database (MTEC, 2009a)
Transportation	1st Data	- Department of Highway
	2nd Data	- Karom, (2008) and Paoluglam (2005)
Waste management		
- 90% Landfill, 10% incineration	1st , 2nd Data	- Experiment and Molgaard (1995)
- Incineration	1st , 2nd Data	- Experiment and Molgaard (1995)
- Incineration with heat recovery	1st , 2nd Data	- Experiment and Molgaard (1995)
- Landfill	1st Data	- Experiment
- Landfill with energy recovery	1st , 2nd Data	- Experiment and Bohlmann (2004)
- Composting	1st Data	- Experiment
- 50% Landfill, 50% incineration	1st , 2nd Data	- Experiment and Molgaard (1995)
- 90% Landfill, 10% incineration	1st , 2nd Data	- Experiment and Molgaard (1995)

Note: * 1st is Primary data.
2nd is Secondary data.

3.3 LCI data of waste management

The following waste treatment scenarios for trays and garbage bags are shown in Table 7.

Table 7 Waste treatment options.

Percentages (%)	Waste management options						
	1	2	3	4	5	6	7
% Landfill	90	–	–	100	–	–	50
% Landfill with heat recovery	–	–	–	–	100	–	–
% Incineration	10	100	–	–	–	–	50
% Incineration with heat recovery	–	–	100	–	–	–	–
% Composting	–	–	–	–	–	100	–

3.3.1 Incineration

The LCI data of incineration was from both Molgaard (1995) and and experiment. Energy consumption for running incineration supplemented Thailand Electricity data. The electricity consumption is 0.05 kWh per kg incinerated plastics. Waste incineration generally produces solid residue during process of 0.25 kg per kg material input (Molgaard, 1995), as shown in Figure 12. The amount of gas combustion for each type of plastics material from incineration plant were calculated in Equation (29), which was according to element analysis (Pichtel, 2005).

$$C_aH_bO_cCl_dF_eN_fS_g + \left(a + \frac{b}{4} - \frac{c}{2} - \frac{d}{2} - \frac{e}{2} + \frac{f}{2}\right)O_2 \rightarrow aCH_4 + \left(\frac{b}{2} - \frac{d}{2} - \frac{e}{2}\right)H_2O + dHCl$$

$$eHF + fNO + gSO_2 \qquad (29)$$

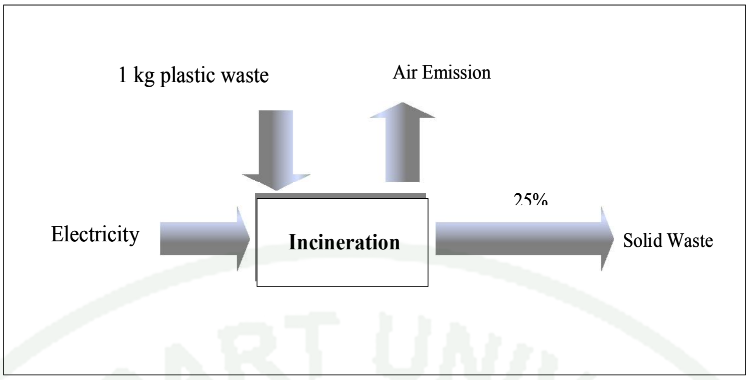


Figure 12 Input and output related to incineration

3.3.2 Incineration and heat recovery

The energy recovery from incineration plant per kg of plastics waste was corresponding in the form of crude oil, natural gas and coal products Molgaard (1995), as shown in Figure 13. The amount of gas combustion from incineration was calculated in Equation 14. The energy content of plastics waste were calculate from the value of element analysis of plastics material (Pichtel, 2005).

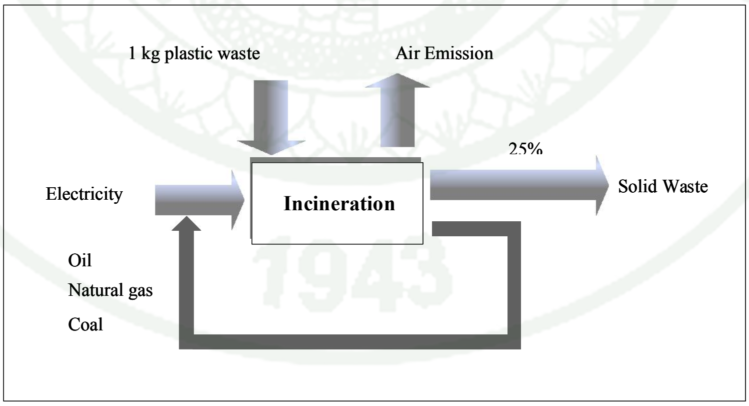


Figure 13 Input and output related to incineration with energy recovery.

3.3.3 Natural landfill in Thailand

The biodegradability potential of biodegradable plastics is performed in an anaerobic degradation condition. The test station at Supan buri province was used to study natural landfill test in Thailand.

1) Materials preparation

The degradability potential under anaerobic landfilling conditions of degradable or biodegradable plastics materials is considered. PLA was purchased from Cargill Dow LLC., and the compression technique was used for preparing PLA sheet. PS was obtained from a tray manufacturing in Thailand. PE/starch (70:30) blend was prepared using twin screw extruder provided by Polymer Chemistry Research Unit (MTEC, Thailand). Plastic sheet was prepared by compression molding in a window mold of 150x150x0.3 mm with molding temperature 180 ^{o}C and pressure 15 tons for ten minutes. PE/TDPA and PE were obtained from garbage bag manufacturing in Thailand.

2) Landfill test

The process begins with preparation pilot scaled-landfill dimention for experiment of (m. x m x m) : 3 x 3 x 1, followed by loading samples, closing landfill and soil coverage, as presented in Figure 14.

(a) (b) (c)

Figure 14 The natural landfill located at Supan buri province, testing in this work. a) Preparation pilot scaled-landfill b) Loading samples c) Closing landfill and soil coverage

Source: Polymer Chemistry Research unit (MTEC, 2009b)

After degradation, the samples were taken outs from the environment and watched with distilled water and dried at vacuum chamber at 50^{O}C for 24 hours. Changes in weight were tested per 2 months during experiment. The pictures were taken before and after biodegradation. The temperature and pH were monitored during experiment.

For municipal solid waste in landfill, the landfill gas generation under anaerobic conditions for plastics includes CO_2 and CH_4 emissions at the ratio of 50% and 50% respectively (Finnveden *et al.,* 1995), as shown in Equation 30.

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} - \frac{e}{2}\right)H_2O \rightarrow \left(\frac{a}{2} - \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + dNH_3 + eH_2S \qquad (30)$$

3.3.4 Composting

The biodegradability potential of biodegradable plastics is performed in an aerobic degradation condition as per ISO 14855-99.

1) Materials preparation

The degradability potential under aerobic composting conditions of degradable and biodegradable plastics materials were considered. PE and MCE were used as negative and positive reference control, respectively. MCE was purchased from Merck & Co., Ltd., which had a particle size of less than 20 µm. PE, PE/starch, and PLA were prepared as samples for landfill testing.

2) Biodegradation test

This study investigated the degradability potential of degradable or biodegradable plastics, namely PE, PE/starch, MCE and PLA. The study was carried out in simulated aerobic degradation condition. The samples were cut into sizes 2.0 x 2.0 cm. Laboratory setup in an aerobic degradation condition was done according to ISO 14855-99. The testing inoculums were obtained from composting of organic agriculture waste. It was utilized as microbial sources in the biodegradation testing. This inoculums were sieved to size less than 10 mm. and stored at 5 ^{o}C for 7 days. The experimental was performed in 2 liters reactors. A series of vessels including blank, positive control, negative control, and test substances were used. They are all in duplicates. Moisture content of composting was adjusted between 50-55% by the addition of deionized water. It was kept in the dark at average temperature of 58.0 ^{o}C (± 2.0 ^{o}C). The air flow rate was controlled in the range of 10 to 40 ml per minutes.

The amount of test mixtures, mixing of inoculums and test materials, were depended on the type of test material. For PLA, test substance (dry matter) was used at the ratio of 60 g to 360 g of inoculums (dry weight). Whereas, PE, PE/starch and MCE were prepared by mixing inoculums (dry weight) of 360 g and test substance (dry matter) of 30 g. The inoculums without any sample were used as blank control and the inoculums with PE or MCE were used as negative and positive reference control, respectively.

The moisture content of the mixtures were adjusted to about 50% before introduced into the reactors. The reactors were placed in the water bath at 58.0 ^{o}C (± 2.0 ^{o}C). The aerobic conditions were maintained during the test throughout each reactor by aerating carbon dioxide–free air. The exhaust air was directly monitored to ensure that oxygen concentration was higher than 6% by using gas analyzer (Gas Data/ Model GSM416 Series).

The theoretical amount of CO_2 ($ThCO_2$), in grams per reactor, was calculated by the following equation:

$$ThCO_2 = M_{TOT} \times C_{TOT} \times \frac{44}{22} \qquad (16)$$

where $ThCO_2$ is the theoretical amount of carbon dioxide which can be produced by the test material, in grams per reactor; M_{TOT} is the total dry solid in grams, in the test material added into the composting reactors at the start of the test; C_{TOT} is the proportion of total organic carbon in the total dry solids in the test material, in grams per gram; 44 and 12 are the molecular mass of carbon dioxide and atomic mass of carbon, respectively.

The carbon dioxide evolution during the biodegradation test was trapped in the 0.1 N $Ba(OH)_2$ and precipitated as $BaCO_3$. The amount of CO_2 evolution was determined by titrating the remaining $Ba(OH)_2$ from each trap with 0.1 N standard HCl to phenolphthalein end–point. The total amount of CO_2 evolution was calculated by reference to blank control reactor.

The percentage of biodegradation of test materials were calculated according to the equation:

$$(\%)\text{Biodegradation} = \frac{(CO_2)_T - (CO_2)_B}{ThCO_2} \times 100 \qquad (17)$$

where $(CO_2)_T$ is the cumulative amount of carbon dioxide evolved in each composting reactor containing test material, in grams per reactor; $(CO_2)_B$ is the mean cumulative amount of carbon dioxide evolved in the blank reactor, in grams per reactors.

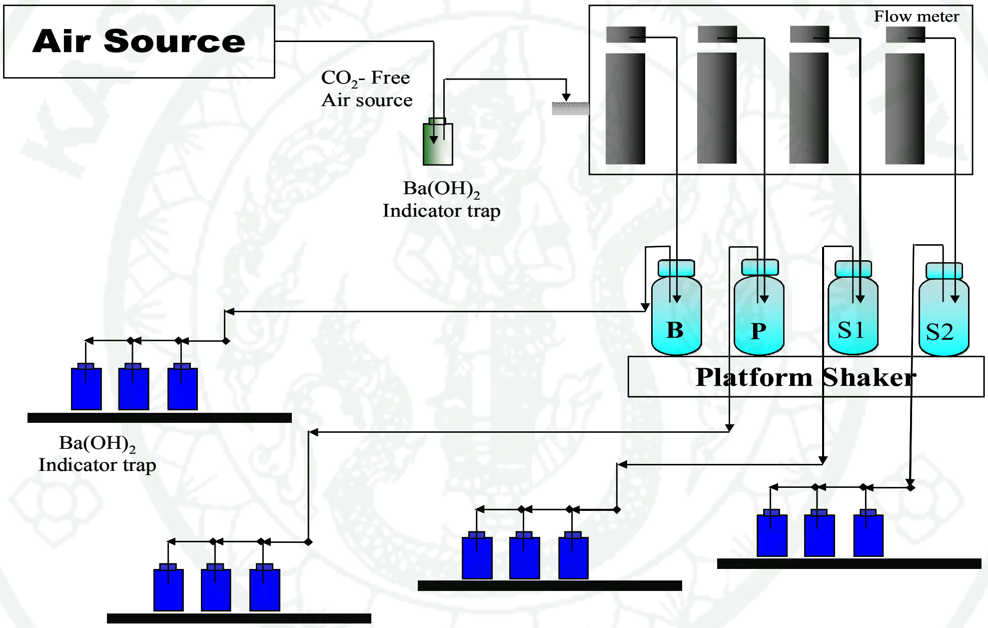


Figure 15 The composting test system as per ISO 14855-99.

4. Life cycle impacts assessment

The LCA methodology is described in the standard EN ISO 14044:2006. The calculation of energy used and environmental impact using the methodology are as follows:

4.1 Energy consumption

This study will investigate the energy consumption of two types of packages. The total energy consumption refers to the amount of total energy required to complete a whole life cycle of packages production. Referring to inventory data, the whole life cycle of trays and garbage bags production consists of six processes. Details of energy used in each process are described as follows:

4.1.1 Raw material extraction ($E_{\text{Raw material}}$)

The energy consumption of raw material extraction consists of energy consumption of two types of renewable resource (corn or cassava cultivation) and two types of petroleum based (crude oil and natural gas extraction).

1) Cultivation ($E_{\text{Cultivation}}$)

The process begins with soil preparation, followed by seeding, fertilization, weeding and harvesting, in turn. The energy and materials used are fuel (diesel and gasoline), fertilizer, and pesticide. Energy consumption in the cultivation process can be calculated from,

$$E_{\text{Cultivation}} = EC_{\text{Fuel}} + EC_{\text{Pesticide}} + EC_{\text{Fertilizer}} \quad (14)$$

According to Eqauation 14, $E_{\text{Cultivation}}$ is the energy consumed in the corn cultivation process in the unit of MJ/420 liters of PLA trays. Energy content (EC) of the materials used in the process is considered at primary energy level and can be calculated by,

$$EC_{\text{Material}} = \text{Quantity of material used} \times \text{Energy content}_{\text{primary energy}} \quad (15)$$

For the fuels,

$$EC_{\text{Fuel}} = \text{Quantity of fuel used} \times \text{Energy content}_{\text{fuel}} \quad (16)$$

2) Crude oil or natural gas extraction ($E_{\text{Crude oil}}$ or $E_{\text{Natural gas}}$)

The fuel (diesel, petroleum gas, residual oil) and chemical are used for crude oil or natural gas extraction. Energy consumption can be calculated from,

$$E_{\text{Crude oil}} = EC_{\text{Fuel}} + EC_{\text{oil}} + EC_{\text{Chemical substances}} \quad (17)$$

$$E_{\text{Natural gas}} = EC_{\text{Fuel}} + EC_{\text{oil}} + EC_{\text{Chemical substances}} \quad (18)$$

4.1.2 Manufacturing ($E_{\text{Manufacturing}}$)

The energy used during manufacturing for packages including material preparation (styrene, ethylene, etc.), PE or PS production (GPPS, HIPS, LDPE, LLDPE and HDPE), cassava starch or PLA production, and tray or garbage bag production. As mentioned above, all most manufacturing consumes electricity, water, steam, chemical substance, etc. Energy consumption in the each manufacturing can be calculated from,

$$E_{\text{Manufacturing}} = EC_{\text{Electricity}} + EC_{\text{Steam}} + EC_{\text{Chemical substances}} \quad (19)$$

and

$$EC_{\text{Electricity}} = (m_{\text{natural gas}} \times EC_{\text{Natural gas}}) + (m_{\text{Coal}} \times EC_{\text{Coal}}) + (m_{\text{oil}} \times EC_{\text{oil}}) \quad (20)$$

where m is the primary amount of resource used to generate electricity.

4.1.3 Transportation ($E_{\text{Transportation}}$)

The raw materials and products are transported different distances. To calculate energy use in the transportation, equation. (20) is used.

$$E_{\text{Transportation}} = [E_R \times D] \times M \quad (21)$$

where E_R is energy consumption rate (MJ/tonnes-km.), D is distance of transportation (km.), M is amount of material transported (tonnes).

The energy consumption rate (E_R) is calculated by,

$$E_R = [F_R \times EC_{Fuel}] / \text{Vehicle capacity} \qquad (22)$$

where F_R is fuel consumption rate (liters/km.), EC_{Fuel} is energy content of fuel (MJ/liters.) and vehicle capacity (tonnes).

4.1.4 Using (E_{Using})

During package usage, there was no input energy or resource using for this phase. Therefore, the energy consumption this phase could be neglected.

4.1.5 Waste management ($E_{Waste\ management}$)

The energy consumption for running waste treatment process was electricity, water, etc. In contrast, alternative waste treatment such as composting and incineration with energy recovery obtained energy.

$$E_{Waste\ management} = EC_{Electricity} + EC_{Water} \qquad (23)$$

4.1.6 Total energy consumption of the tray and garbage bag

Summation of the energy use in each process results in the total energy use through the whole life cycle of the tray and garbage bag. Therefore, the total energy consumption for PLA and PS trays can be calculated using Equation. 24 and 25 as follows,

$$\mathbf{E}_{PLA} = E_{Cultivation} + E_{PLA\ production} + E_{tray\ production} + E_{Using} + E_{Transportation} + E_{End\ of\ life} \qquad (24)$$

$$\mathbf{E}_{PS} = E_{Raw\ material} + E_{material\ preparation} + E_{PS\ production} + E_{tray\ production} + E_{Using} + E_{Transportation} + E_{End\ of\ life} \qquad (25)$$

and the total energy consumption for garbage bag such as PE/starch and PE, the calculation can be written as

$$\mathbf{E}_{PE/starch} = E_{Raw\ material} + E_{material\ preparation} + E_{PE\ or\ starch\ production} + E_{bag\ production} + E_{Using} + E_{Transportation} + E_{End\ of\ life} \qquad (26)$$

$$\mathbf{E}_{PE} = E_{Raw\ material} + E_{material\ preparation} + E_{PEproduction} + E_{bag\ production} + E_{Using} + E_{Transportation} + E_{End\ of\ life} \qquad (27)$$

4.2 Environmental impact assessment

CML Baseline 2000 (Update CML version 3.2) method is used in this work. This method focuses on 11 categories of environmental impacts, as shown in Table 8. For CML method, it was focused on characterization which gave the result of impact categories in kg equivalent unit. Normalization was carried out from Centre of Environmental Science, in the Netherland. Moreover, Guineee *et al*. (2001) have developed a weighting method that can be used with the CML method. This weighting method is based on a panel procedure developed in the Netherlands.

Table 8 Type of environmental impacts, normalization factor, and weighting value of CML 2 Baseline 2000 method.

Environmental Impact	Characterizaton Unit	Normalized Value	Weighted Value
Abiotic depletion	kg Sb eq.	6.39E-12	25.86
Global warming	kg CO_2 eq.	2.41E-14	20.00
Ozone layer depletion	kg CFC11 eq.	1.94E-09	4.04
Human toxicity	kg 1,4-DB eq.	1.75E-14	10.51
Fresh water aquatic ecotoxity	kg 1,4-DB eq.	4.90E-13	4.85
Marine aquatic ecotoxicity	kg 1,4-DB eq.	1.95E-15	6.46
Terrestrial ecotoxicity	kg 1,4-DB eq.	3.72E-12	12.93
Photochemical oxidation	kg C_2H_4 eq.	1.04E-11	4.04
Acidification	kg SO_2 eq.	3.11E-12	6.46
Eutrophication	kg PO_4 eq.	7.56E-12	4.85
Land used	m^2·year	8.06E-15	10.60

4.3 Methodology of CML method in SimaPro 7.02

The impact assessment component of an LCA is defined as a quantitative and/or qualitative process to identify, characterize and assess the potential impacts of the environmental interventions identified in the inventory analysis. According to the impact assessment by CML2 Baseline 2000 (Update CML version 3.2) method consists of three distinct steps:

- Characterization
- Normalization
- Weighting.

4.3.1 Characterization step, which take into account both the magnitude and potency of the inventory categories. The potential contribution to each environmental impact category is quantified.

$$EP_j = (Q_i \times EF_{ij}) \tag{28}$$

where EP_j is environmental impacts potential (kg substance equivalent), Q_i is quantities of substance (kg substance j), EF_{ij} is substance equivalency factor (kg substance equivalent/ kg substance j).

4.3.2 Normalization is an optional step and is carried out in order to normalize the data from the characterization step in relation to the actual magnitude of the impacts in some given area, making it easier to understand the relative magnitude of each environmental impact score.

$$NP_j = EP_j / (T \times ER_j) \tag{29}$$

where T is lifetime of product (year), ER_j is normalization reference (kg substance/person/year).

4.3.3 Weighting, directly follows the classification and characterization steps, with this stage being a subjective analysis of how the different environmental problems should be weighted against each other. These weighting factors may be established in a panel, either on the national, regional or global level, with the general idea being to directly investigate the preferences of society for reduction of environmental impacts.

$$WP_j = WF_j \times NP_j \tag{30}$$

where WP_j is weighted environmental impact potential (person for target year; Pt), WF_i is weighing factor.

4.4 Carbon footprint analysis

Product carbon footprinting (PCF) has emerged as a tool to assess the life cycle greenhouse gas emissions associated with the life cycle of product, expressed in terms of kg CO_2 equivalent per functional unit. The carbon footprint is quantified using indicators such as the Global Warming Potential (GWP) (IPCC, 2007). GWP is an indicator that reflects the relative effect of a greenhouse gas in terms of climate change considering a fixed time period, such as 100 years (GWP_{100}). The sum of carbon footprint (greenhouse gases) from the life cycle of product is shown in Equation 49.

$$\text{Carbon footprint (total)} = \sum [GHG_T \times \text{GWP equivalency factors}] \qquad (31)$$

where GHG_T is total GHG emission in each life cycle stage (kg), GWP (100 years) equivalency factors refer to the global warming potentials of GHG emissions (IPCC, 2007),

5. Biodegradable kinetic of plastics under controlled composting conditions

This study aims to propose and evaluate the kinetics of C-CO_2 evolution during biodegradation of plastic materials including Polyethylene (PE), microcrystalline cellulose (MCE), PE/starch blend (PE/starch), and Polybasic acid (PLA). The aerobic biodegradation under controlled composting conditions was monitorated according to ISO 14855-99. The kinetics model was based on first order reaction in series with a flat lag phase. Non- linear regression analysis was used to calculate the results. SEM morphology of the samples before and after biodegradation test was used to confirm the model results.

RESULTS AND DISCUSSION

1. LCI data and environmental impact of trays packages

The LCI data from the production of trays consist of six stage including raw materials extraction, raw materials preparation, GPPS, HIPS and PLA production, tray manufacturing, using, and transportation. Tray production consists of four main steps including mixing, extrusion, thermoforming and cutting, and packaging. Plastic pellets were mixed in the mixing machine and melted in the extrusion machine to give the formulated plastic pellets which were shaped into tray by thermoforming process and then cut and packaged. No recycling process is considered in this study. Figure 16 shows a typical process flow diagram of tray production. Detailed information of LCI in each type of trays are described as follows:

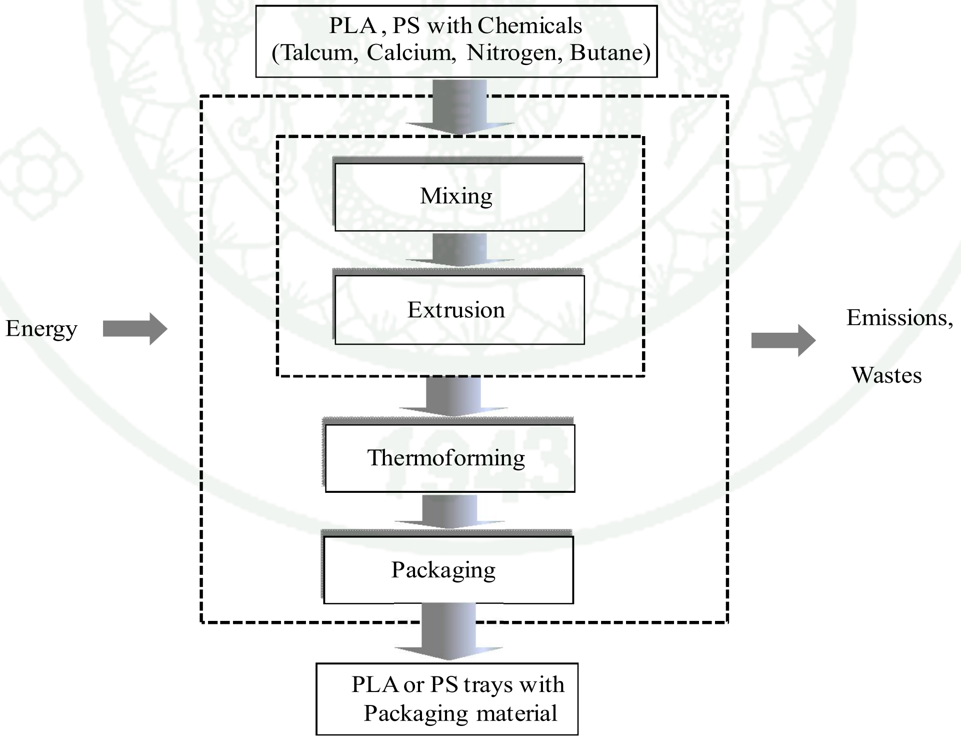


Figure 16 Typical process flow of tray production.

1.1 LCI data of trays Package

1.1.1 LCI of PLA trays

The LCI data from the production of PLA tray consist of five stage including corn production, PLA pellets production (dextrose, lactic acid, and PLA production), trays manufacturing, using and transportation. Detailed information of LCI in each process are described as follow:

1) Corn plantation

The LCI data of corn cultivation are carried out by collecting the necessary information from SimaPro 7.0 database**.** Data was collected from corn cultivation in the USA. Corn growing includes inputs such as corn seed, fertilizer, pesticides, and fuel (diesel) used by farmer, land used and CO_2 absorption through the photosynthesis process. Detailed information of corn cultivation in USA is shown in Appendix Table B1.

2) PLA production

The PLA pellets production data (dextrose, lactic acid, and PLA production) were collected by Vink *et al.,* (2003) based on the production of 2003. The PLA pellets were supplemented from Cargill Dow at the Blair, Nebraska, USA. The amount of raw materials and energy used from PLA pellets production were expressed in the unit of electricity and natural gas at ratio of 1 to1 (Johansson, 2005), as shown in Table 9. Input and output of PLA production is shown in Figure 17. PLA production include, processing of corn into dextrose, processing of dextrose in to lactic acid by utilizing fermentation, conversion of lactic acid into lactide, and polymerization of lactide into polylactide. The pellets are the final stage of the PLA.

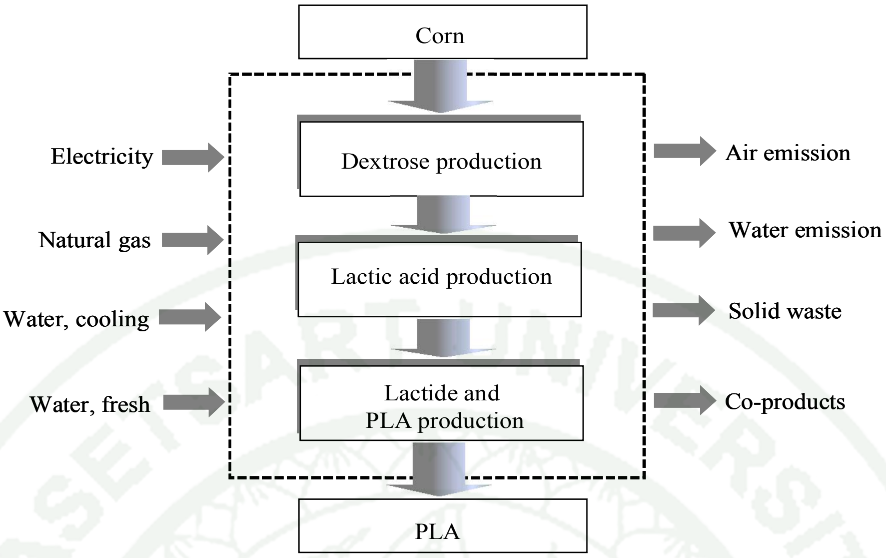


Figure 17 Input-output of PLA production

Table 9 LCI data of PLA production (1,000 kg of PLA).

Item	Amount	Unit
Mass/Energy input		
Corn	1,656.80	kg
Water, cooling, surface	7,850.00	kg
Water (irrigation)	32,100.00	kg
Electricity	6,569.00	kWh
Natural gas	24,194.00	MJ
Mass/Energy output		
PLA	1,000	kg
Solid waste		
Residue (Corn)	98.10	kg
Residue (Lactic acid)	50.00	kg
Residue (Dextrose)	90.00	kg

3) PLA tray production

The LCI data were obtained from the National Metal and Materials Technology Center (MTEC), which was also collected from a pilot scale manufacturing of the PLA tray in 2007. Detailed information of PLA tray production is shown in Figure 16 and Table 10.

Table 10 LCI data of PLA tray production per functional unit.

Item	Amount	Unit
Mass/Energy input		
PLA	15.207	kg
PLA (recycle)	2.509	kg
Electricity	30.263	kg
PE Bags	0.0730	kg
Glue	1.23E-03	kg
Mass/Energy output		
PLA trays	1,000	pcs.
Solid waste		
Waste (PLA)	0.2774	kg
Scrap (PLA)	2.7599	kg

4) Using

The avoided energy used or waste generation during used for PLA trays. Therefore, the LCI result shows that PLA trays contribute a zero energy used and emissions. This study presumes that distance from tray factory to user is completely 20 km. Information of PLA tray transportation into user was calculated based on distance from PLA tray factory to user are summarized in Appendix Table B2.

5) Transportation

Detailed of distance raw materials to tray production is summarized in Appendix Table B2. Information of PLA transportation was calculated based on distance from Nebraska in USA to Rayong province in Thailand. This study presumes that corn seeding, corn plantation, and PLA production located the in the same province. Therefore, distance from corn seeding to corn plantation or distance from corn to PLA production was 20 km. PE package was supplemented from bag manufacturing, which mostly located in Bangkok and Nakornpatom.

1.1.2 LCI data of PS trays

The LCI data from the production of PS trays consist of six stage including raw materials extraction (crude oil and natural gas), raw materials preparation (styrene monomer, ethyl benzene, naphtha, polybutadiene rubber and peroxide), GPPS and HIPS production, tray manufacturing, using, and transportation. Detailed information of LCI in each process are described as follow:

1) Raw material extraction

- Crude oil exploration

The LCI of crude oil exploration was carried out by collecting the necessary information from SimaPro 7.0 database**.** Data collected from crude oil exploration in Middle East Asia. Detailed information of crude oil exploration production in Middle East Asia is shown in Appendix Table C 1.

- Natural gas offshore

The LCI of natural gas offshore was carried out by collecting the necessary information from SimaPro 7.0 database. Data collected from natural offshore in Europe. Detailed information of natural offshore in Europe is shown in Appendix Table C2.

2) Raw materials preparation

Input raw materials for formulation GPPS and HIPS pellets are generally included: styrene monomer, ethyl benzene, naphtha, polybutadiene rubber, and initiator (organic peroxide). The LCI of styrene monomer, ethyl benzene, naphtha, polybutadiene rubber, and initiator (organic peroxide) production were carried out by collecting the necessary information from SimaPro 7.0.

3) PS pellets production

- GPPS pellets production

GPPS production involves mixing of formulated raw materials by Dow Chemical Company with styrene monomer, ethyl benzene, and initiator (organic peroxide). The inventory includes all processes which involve a production of formulated GPPS at Dow Chemical Company to get GPPS pellets Paoluglam (2005). Appendix Table C 3 shows the overall input-output of GPPS production 1,000 kg.

- HIPS pellets production

HIPS production involves mixing of formulated raw material by Dow Chemical Company with styrene monomer, ethyl benzene, initiator (organic peroxide), and polybutadiene rubber. The inventory includes all processes which involve a production of formulated HIPS at Dow Chemical Company to get HIPS pellets Paoluglam (2005). Appendix Table C 4 shows the overall input-output of HIPS production 1,000 kg.

4) PS tray production

LCI data of tray production was obtained from Asia Plus Pack Co. Ltd., at Samutprakarn Province. PS pellets with chemicals (talcum and nitrogen) were mixed in the mixing machine and melted in the extrusion machine with butane gas to give the formulated plastic pellets which were shaped into tray by thermoforming process and then cut and packaged. Detailed information of PS tray production is shown in Figure 16 and Table 11.

Table 11 LCI data of PS tray production (1,000 pcs. of PS tray).

Item	Amount	Unit
Mass/Energy input		
Talcum	0.01833	kg
Calcium	0.00204	kg
Butane	0.3783	kg
Nitrogen	0.0163	m^3
Virgin GPPS pellets	6.3302	kg
Virgin HIPS pellets	0.4415	kg
PE Bags	0.073	kg
Glue	1.23E-03	kg
Electricity	1.0000	kWh
Mass/Energy output		
PS trays (1,000 pcs.)	4.0337	kg
Air emissions		
Butane	1.881E-01	kg
Nitrogen	1.63E-02	m^3
Solid waste		
Waste color	4.71E-05	kg
Scrap plastics	2.9474	kg

5) Using

The avoided energy used or waste generation during used for PS trays. Therefore, the LCI result shows that PS tray contributes a zero energy used and emissions. This study presumes that distance from PS tray factory to user is completely 20 km. Information of PS tray transportation into user was calculated based on distance from PS tray factory to user are summarized in Appendix Table C5.

6) Transportation

Detailed of raw materials in the entire life cycle of PS trays are described as follows:

Information of crude oil transportation was reviewed from secondary data source and calculated based on average distance of crude oil transportation import from Middle East, Far East Asia, and gulf of Thailand (Erawan) to Rayong province. LCI data of crude oil transportation are shown in Appendix Table C5.

Information of natural gas transportation was reviewed from secondary data source and calculated based on average distance of natural gas transportation from gulf of Thailand to natural gas separation plant in Rayong province (Karom, 2009). LCI data of natural gas transportation are shown in Appendix Table C 6.

Distance of materials transportation for GPPS and HIPS production are shown in Appendix Table C7. Information of GPPS and HIPS pellets transportation were calculated based on average distance from Rayong province to PS tray factories in Thailand, as shown in Appendix Table C8. Distance of materials transportation to PS tray factories are shown in Appendix Table C 9.

1.1.3 Distance to waste management of PLA and PS trays

Distance between center of waste collection to incineration plant are average from distance between Bangkok to Samut-Prakan province (PCD, 2007), while distance to compost or landfill site is average from distance between Bangkok to Chachoengsao and Nakhonpathom province (PCD, 2007).

Distance for transportation to waste management of PLA and PS trays are based on average distance in Thailand, as shown in Table 12.

Table 12 Distance of PLA and PS trays transportation to municipal solid waste (MSW).

Original-Destination	Amount (kg)		vehicle	Distance 1 way (km)
	PLA	PS		
Waste collection (Bangkok)- Incineration	15.10	4.03	Truck	21.94
Waste collection (Bangkok)-Compost	15.10	4.03	Truck	97.85
Waste collection (Bangkok)-Landfill	15.10	4.03	Truck	97.85

1.1.4 Waste management of PLA and PS trays

The following waste treatment options for both PS and PLA are considered. The LCI data of waste management scenarios in this section are summarized as follows:

1) 90% landfill and 10% incineration of PLA and PS (option1)

Currently, almost of all municipal solid waste (MSW) in Thailand is disposed of in landfill of 90% and incineration of 10% (Paoluglam, 2005). The LCI data of landfill and incineration of PLA and PS trays are shown in Table 13.

2) Incineration of PLA and PS (option2)

The LCI data of incineration and heat recovery are from both experiment and Molgaard (1995). Detailed information of incineration for both PLA and PS trays are shown in Table 14.

3) Incineration and heat recovery of PLA and PS (option3)

The LCI data of incineration and heat recovery are from both experiment and Molgaard (1995). The LCI data of incineration and heat recovery for both PLA and PS trays are shown in Table 15.

Table 13 LCI data of landfill of 90% and incineration of 10% per functional unit of PLA and PS trays.

Type	PLA	PS	Unit
Mass/Energy input			
Waste	15.10	4.03	kg
Electricity	0.075	0.002	kWh
Land used for landfill	0	24.42	m^2
Land used for incineration	0.70	0.70	m^2
Mass/Energy output			
Air emissions			
CO_2 emission	18.689	1.347	kg
CH_4 emission	5.062	0.059	kg
Solid waste			
Waste from landfill	0	0.100	kg
Waste from incineration	0.377	3.518	kg

Table 14 LCI data of incineration per functional unit of PLA and PS trays.

Type	PLA	PS	Unit
Mass/Energy input			
Waste	15.10	4.03	kg
Electricity	2.718	0.202	kWh
Land used for incineration	7.0	7.0	m^2
Mass/Energy output			
Air emissions			
CO_2 emission	25.690	11.832	kg
Solid waste			
Waste from incineration	3.775	1.008	kg

Table 15 LCI data of incineration and heat recovery per functional unit of PLA and PS trays.

Type	PLA	PS	Unit
Mass/Energy input			
Waste	15.10	4.03	kg
Electricity	0.075	0.002	kWh
Land used for incineration	0.70	0.70	m^2
Mass/Energy output			
Crude oil	-5.061	-3.030	kg
Natural gas	-1.888	-1.132	kg
Coal	-0.608	-0.362	kg
Air emissions			
CO_2 emission	25.690	11.832	kg
Solid waste			
Waste from incineration	3.775	1.008	kg

4) Landfill of PLA and PS (option4)

The results of temperature and pH during landfill test are shown in Table 16, which indicate that the temperature of landfill is in the range of 32.5-62^{O}C of enzymatic degradation (Lenz, 1993). Average pH is 8.03-8.36 (8.13) in the natural landfill, which is quite appropriate for enzymatic degradation (pH 5-8) (Lenz, 1993). The results of weight changes of PLA and PS samples after incubation in the landfilling are presented in Figure 18. Although the landfill conditions are favorable condition for microbial activity, the weight loss of PS is only 3.10% after 20 months. Whereas, the biodegradation of PLA can be visually detected within 4 months and the full degradation of PLA could be observed within 16 months. There are low amounts of weight changes of PS, which consistent with Finnveden *et al.* (1995). An example of picture (images) of the samples studied both PLA and PS under landfill condition as a function of time is present in Figure 19 and Figure 20, respectively. The LCI data of PLA and PS from the natural landfill carried out in Thailand of 20 months, as shown in Table 17.

Table 16 Temperature and pH during landfill test.

Months	Temperature	pH
2 Months (June-August)	32.5-34.5	8.05
4 Months (August-September)	32.5-34.5	8.21
6 Months (October-November)	32.5-34.5	8.36
8 Months (November-January)	59-62	8.25
10 Months (January -May)	32.5-62	8.03
14 Months (May-July)	32.5-62	8.10
16 Months (July- November)	59-62	8.12
18 Months (November-January)	59-62	8.03
20 Months (January-March)	59-62	8.03

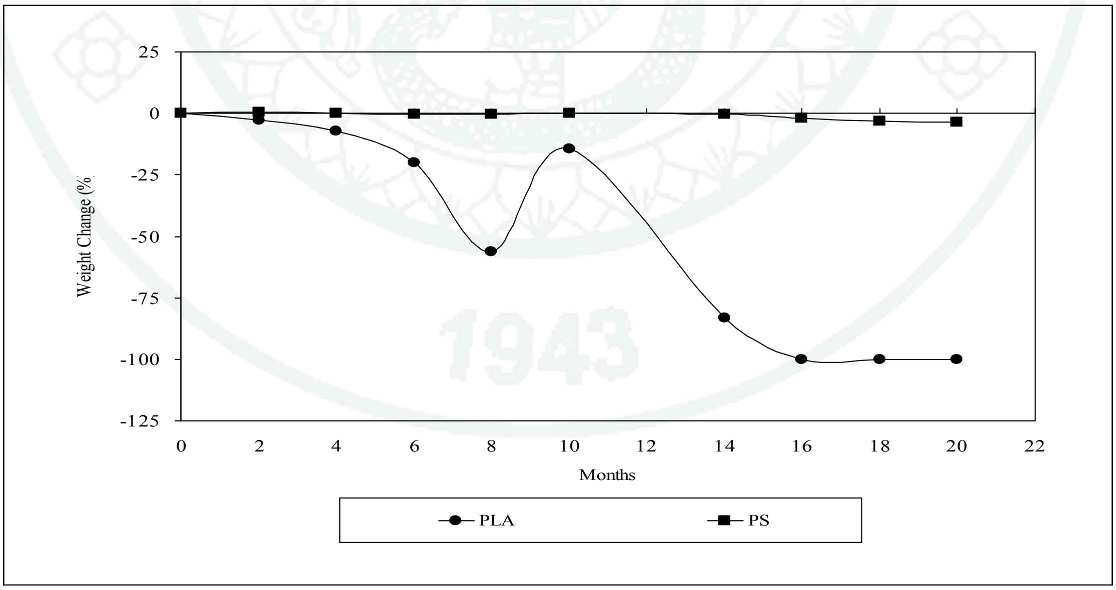


Figure 18 Weight changes of PLA and PS after incubation in the landfill as a function of time.

Table 17 LCI data of landfill per functional unit of PLA and PS trays.

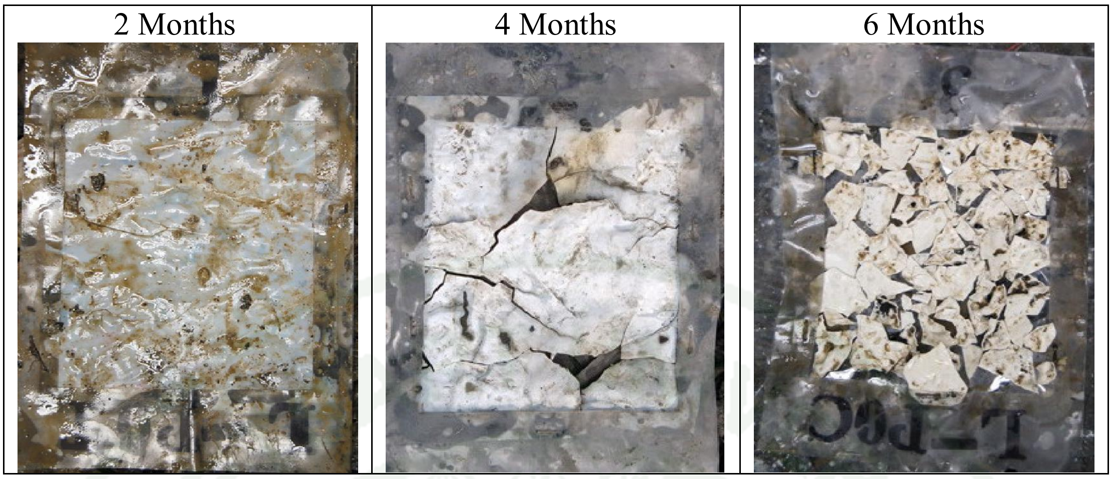
Type	PLA	PS	Unit
Mass/Energy input			
Waste	15.10	4.03	kg
Land used for landfill	0	27.134	m^2
Mass/Energy output			
CO_2 emission	17.911	0.183	kg
CH_4 emission	6.513	0.066	kg
Solid waste			
Waste from landfill	0	3.909	kg

5) Landfill with energy recovery from methane collection (option5)

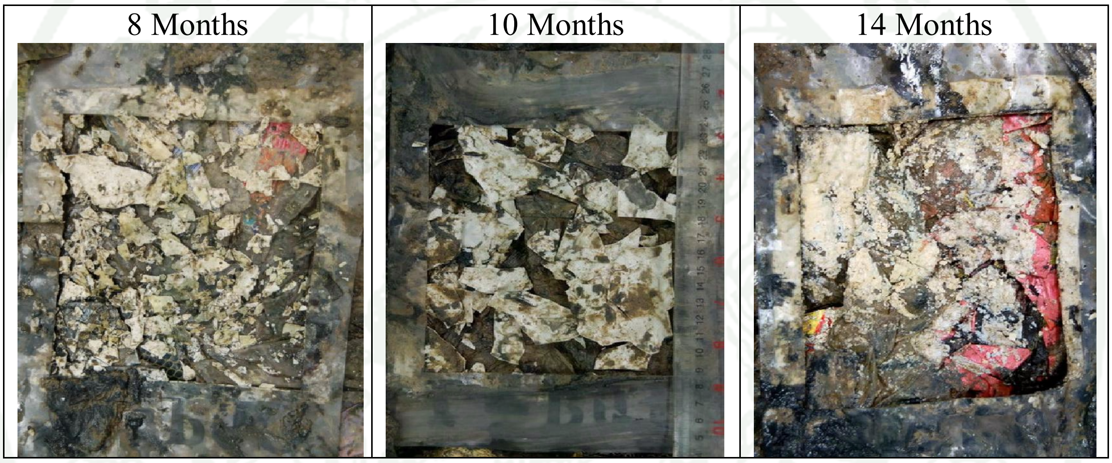
The LCI data of Landfill with energy recovery from methane collection was from both experiment and Bohmann (2004). The LCI data of the calculation are summarized in Table 18.

Table 18 LCI data of landfill with energy recovery per functional unit of PLA and PS trays.

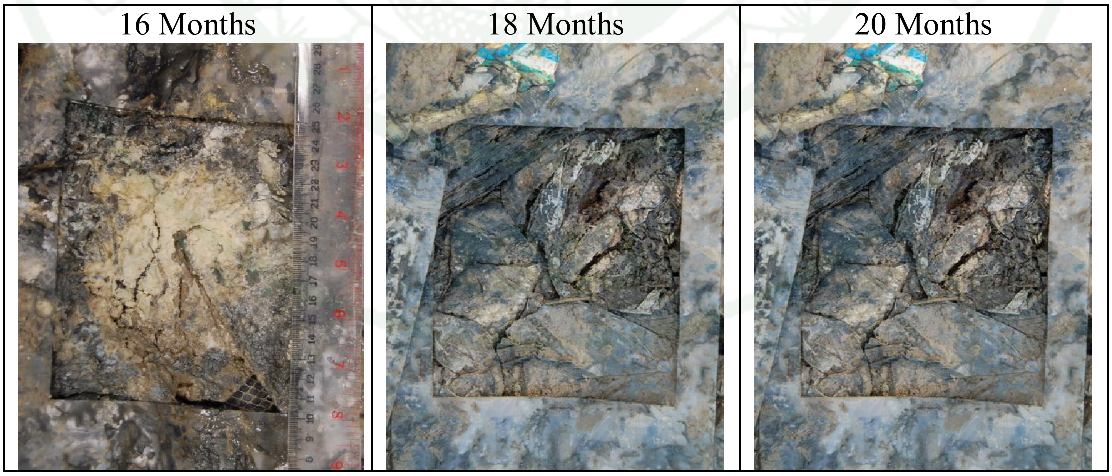
Type	PLA	PS	Unit
Mass/Energy input			
Waste	15.10	4.03	kg
Land used for landfill	0	27.134	M2
Mass/Energy output			
Electricity	-44.87	-0.45	kWh
CO_2 emission	17.911	0.183	kg
CH_4 emission	1.628	0.002	kg
Solid waste			
Waste from landfill	0	3.909	kg



2 Months | 4 Months | 6 Months

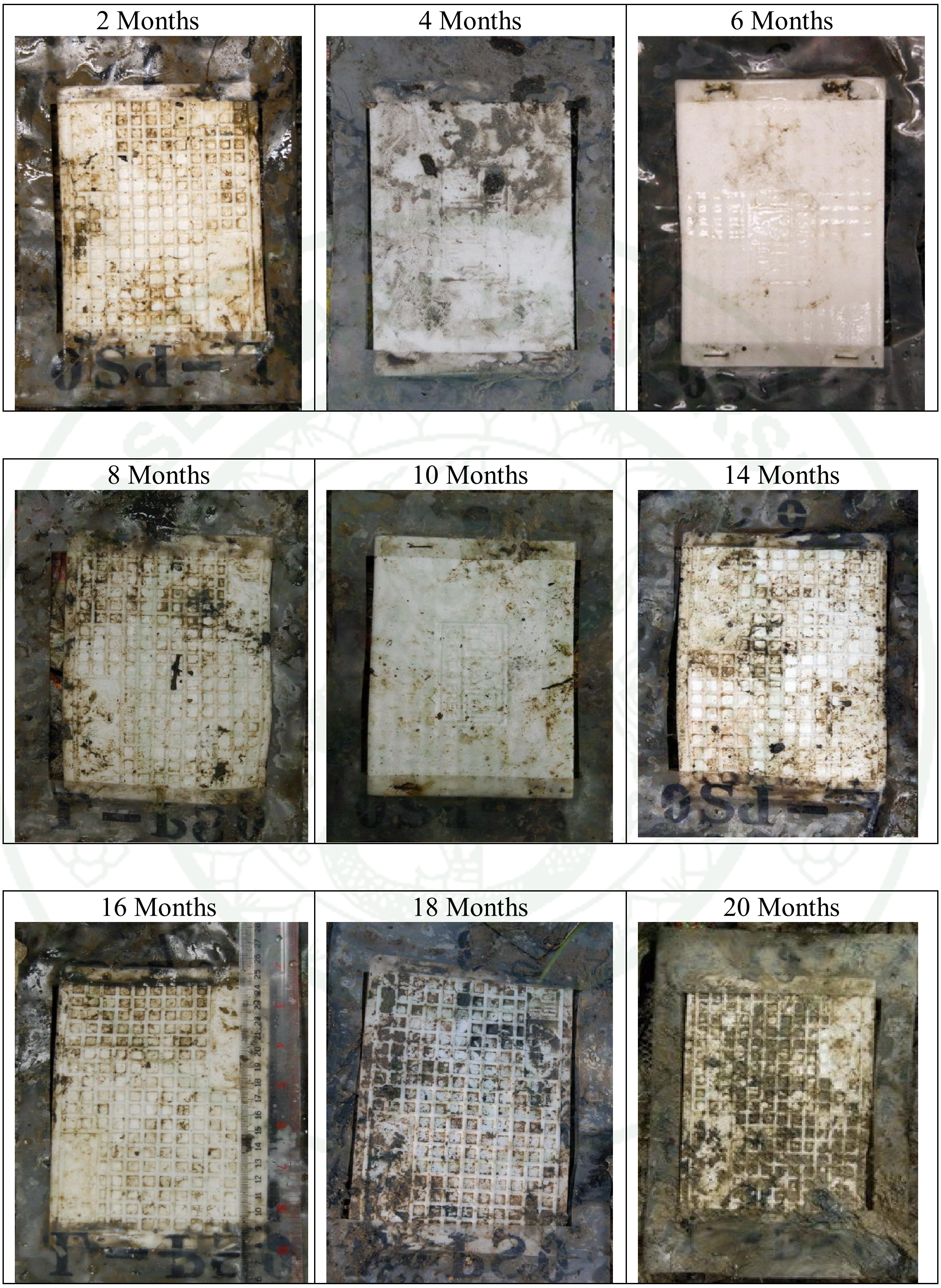


8 Months | 10 Months | 14 Months



16 Months | 18 Months | 20 Months

Figure 19 Degradation of PLA sheets under landfill conditions as a function of time.



2 Months
4 Months
6 Months
8 Months
10 Months
14 Months
16 Months
18 Months
20 Months

Figure 20 Degradation of PS sheets under landfill conditions as a function of time.

6) Composting of PLA and PS (option6)

The biodegradability potential of PLA is performed in an aerobic degradation condition as per ISO 14855-99. The testing soil was obtained from compost of organic agricultural waste. As composting is an aerobic biological treatment, it presumes that CH_4 emissions are not generated. The biodegradability potential of PS was supplemented data from compost PE, which was about 0.56 %. The biodegradability potential of PLA is 85.75%. The bonuses obtain from composting treatment for agriculture: fertilizers (N-P-K), and carbon sequestration (Razza *et al.,* 2009) for PLA because the biodegradability potential closes 90% (ISO 14855-99). Carbon sequestration obtained from organic carbon of the compost of 11.26% (Bohlmann, 2004). Similarly, this is interesting to assess the heavy metal in the compost. Detailed information of composting obtained from PLA and PS trays are shown in Table 19.

7) Landfill 50% and incineration 50% of PLA and PS trays (option7)

The disposal in USA and Singapore, the municipal solid waste (MSW) are disposed in 50% landfill and 50% incineration of 50% (Tan and Khoo, 2005). The LCI data of 50% landfill and 50% incineration of PLA and PS are shown in Table 20.

Table 19 LCI data of composting per functional unit of PLA and PS trays.

Type	PLA	PS	Unit
Mass/Energy input			
Waste	15.10	4.03	kg
Organic agricultural waste	90.60	24.18	kg
Air	*76.81	**0.207	kg
Land used	16.779	26.494	m^2
Mass/Energy output			
Air emissions			
CO_2 emission	22.18	0.06	kg
Emissions to soil			
Compost	99.65	24.394	kg
- Waste plastics	9.05	3.816	kg
- Fertilizer N	0.996	–	kg
- Fertilizer P	0.596	–	kg
- Fertilizer K	0.657	–	kg
- Carbon sequestration	11.22	–	kg
- As	2.72E-04	–	kg
- Cd	8.97E-06	–	kg
- Cr	0.00E+00	5.22E-05	kg
- Cu	4.14E-03	–	kg
- Cd	0.00E+00	–	kg
- Hg	0.00E+00	3.13E-05	kg
- Pb	4.12E-03	–	kg
- Zn	2.72E-04	–	kg

Note : *Air consists of oxygen and nitrogen 16.13 kg and 60.68 kg, respectively.

**Air consists of oxygen and nitrogen 4.36E-02 kg and 1.64E-01 kg, respectively.

Table 20 LCI data of landfill of 50% and incineration of 50% per functional unit of PLA and PS trays.

Type	PLA	PS	Unit
Mass/Energy input			
Waste	15.10	4.03	kg
Electricity	0.3775	0.1001	kWh
Land used for landfill	0	13.56	m^2
Land used for incineration	3.50	3.50	m^2
Mass/Energy output			
Air emissions			
CO_2 emission	21.801	6.007	kg
CH_4 emission	3.256	0.033	kg
Solid waste			
Waste from landfill	0	1.954	kg
Waste from incineration	1.887	0.504	kg

1.2 Energy consumption of PLA and PS trays

The results of energy consumption of two types of trays are shown in Figure 21. It is found that energy consumption for PLA trays is 1.124x10^3 MJ/FU. Among the total energy consumption for PLA trays, approximately 75.8 % comes from PLA production, followed by corn plantation and tray production, respectively. Considering the PLA production, the highest portion of energy consumption comes from the use of electricity and natural gas, which accounts for 49.0% and 50.0%, respectively.

It is found that energy consumption for PS trays is 5.961 x10^2 MJ/FU. Among the total energy consumption for PS trays, approximately 69.2% comes from raw material extraction (crude oil and natural gas), followed by PS production and tray production, respectively. Considering raw material extraction, the highest portion of energy consumption comes from the use of crude oil and natural gas, which accounts for 65.2% and 34.8%, respectively.

The comparison of energy consumption of PLA and PS trays, it is found that total energy consumption of PLA trays is higher than those PS trays of 1.88 times. As above results, the highest portion of energy consumption of PLA trays come from the use of electricity and natural gas in PLA production while PS trays come from crude oil and natural gas extraction.

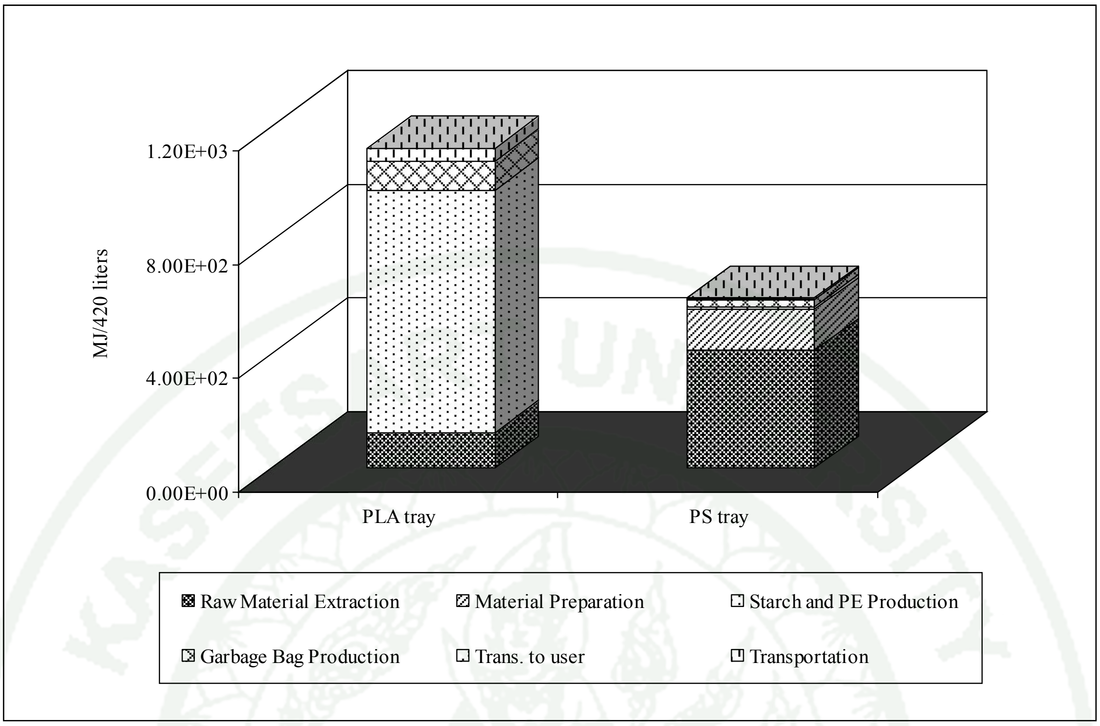


Figure 21 Comparison of the contribution of energy consumption in each phase of PLA and PS trays (cradle-to-gate).

1.3 Environmental impacts (characterization value) of PLA trays

The assessments of environmental impact (characterization value) in the life cycle assessment (LCA) of PLA trays are considered. It is found that the entire life cycle of PLA trays, in almost all impact categories, corn plantation and PLA production contribute the highest environmental impact, as shown in Figure 22. Similarly, the percentage of environmental impact potentials (characterization value), it can be clearly observed that corn plantation and PLA production contribute the highest environmental impact potentials in the most impact categories. Besides, transportation stage reveals the high contribution for ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, and photochemical oxidation.

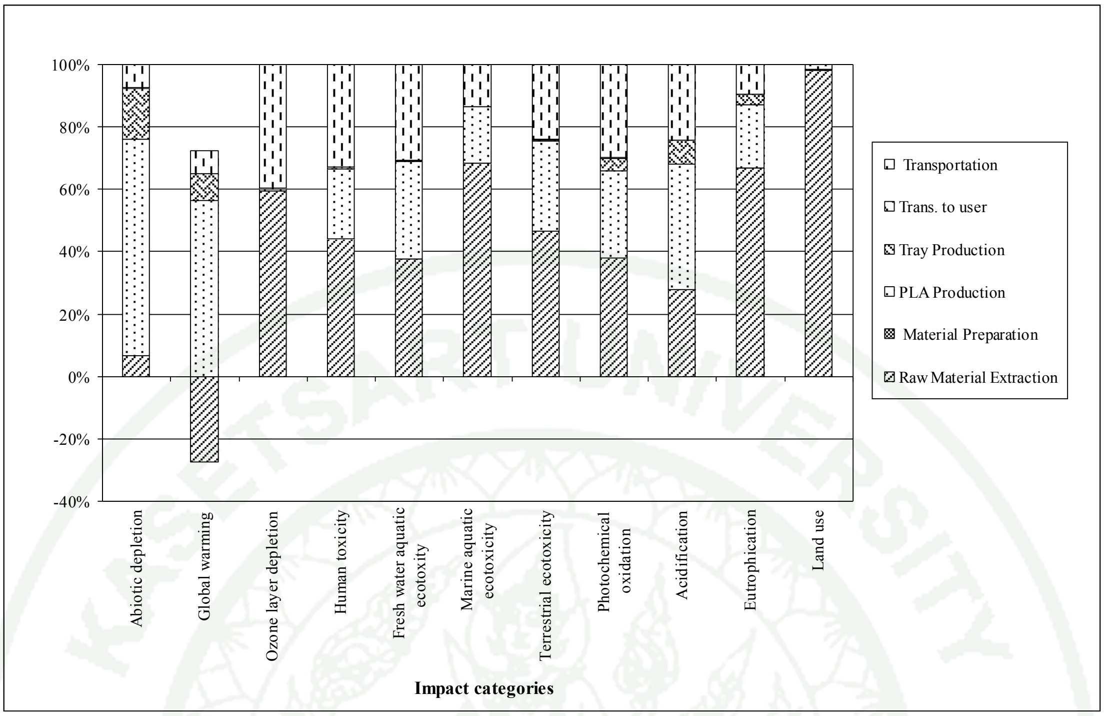


Figure 22 Contribution of the characterization value of each impact categories in PLA trays (cradle-to-gate).

1.4 Environmental impacts (characterization value) of PS trays

The assessments of environmental impact (characterization value) in the life cycle assessment (LCA) of PS trays are shown in Figure 23. The assessment includes crude oil and natural gas extraction, raw material preparation (styrene monomer, ethyl benzene, naphtha, polybutadiene rubber, and initiator), GPPS and HIP pellets production, tray manufacturing, using, and transportation. It is found that the entire life cycle of PS tray, crude oil and natural gas extraction and raw materials preparation contribute the highest environmental impact in almost all impact categories. Similarly, the percentage of environmental impact potentials (characterization value), it can be clearly observed that crude oil and natural gas extraction and raw material preparation give the highest environmental impact potentials in most impact categories. Besides, transportation stage and PS pellets production stage reveals the high contribution for human toxicity and photochemical oxidation, respectively.

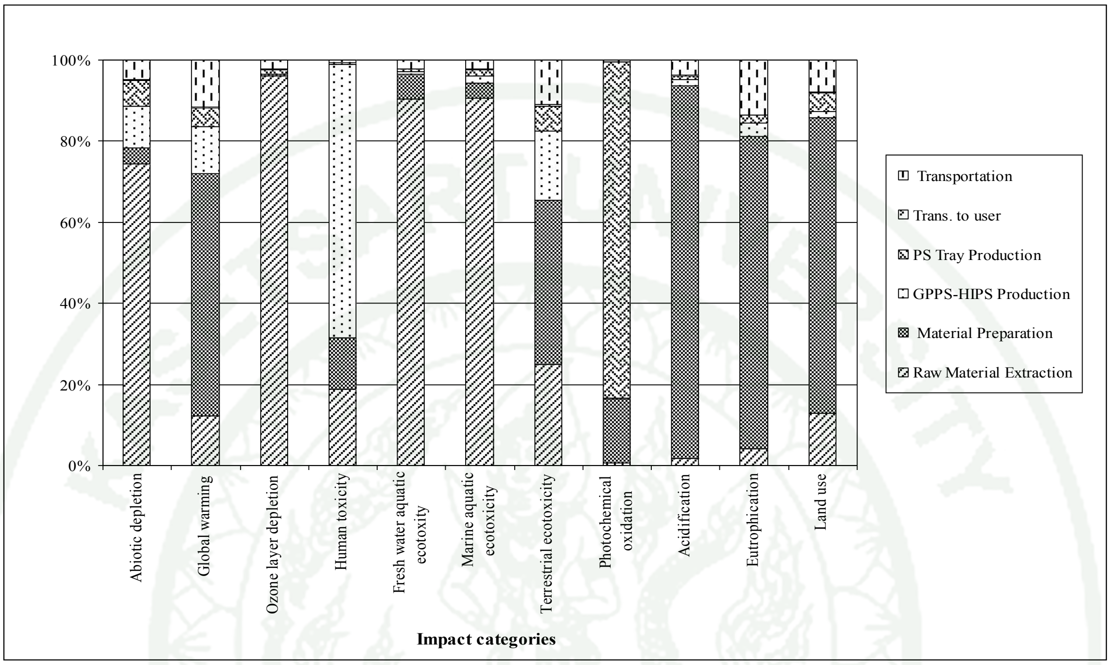


Figure 23 Contribution of the characterization value of each impact categories in PS trays (cradle-to-gate).

1.5 Comparison of environmental impact of PLA and PS trays

The comparison of environmental impact from cradle to gate factory, the percentage of environmental impact potentials (characterization value) is shown in Figure 24. It could be clearly found that PLA trays have higher environmental impact than PS trays in all categories, except ozone layer depletion human toxicity and photochemical oxidation impact. As mentioned above, the high contribution in human toxicity and photochemical oxidation impact of PS trays come from emission from electricity and hydrocarbon of PS production and butane from tray production. Major cause of high ozone layer depletion impact for PS trays comes from crude oil exploration.

Figure 25 shows environmental impact potentials of all impact categories, which are grouped into the single score or the total environmental impact. It is found that the total environmental impact of PLA trays is higher than those PS trays of 2.57 times. It clearly observed that total environmental impact score of PLA trays are from PLA production and corn plantation, approximately 50.2% and 28.9%, respectively. For PS trays, the causes of total environmental impact score obtain from crude oil and natural gas extraction and material preparation of 74.1% and 11.2%, respectively. From Figure 26, it can be clearly observed that PLA production gives the highest environmental impact potentials in most impact categories. Considering PLA trays, the main load comes from abiotic depletion, marine aquatic ecotoxicity, and global warming, which accounts for 93.26%. The main environmental impacts for PS trays are also dominated by abiotic depletion marine aquatic ecotoxicity, and global warming, approximately 85.6%.

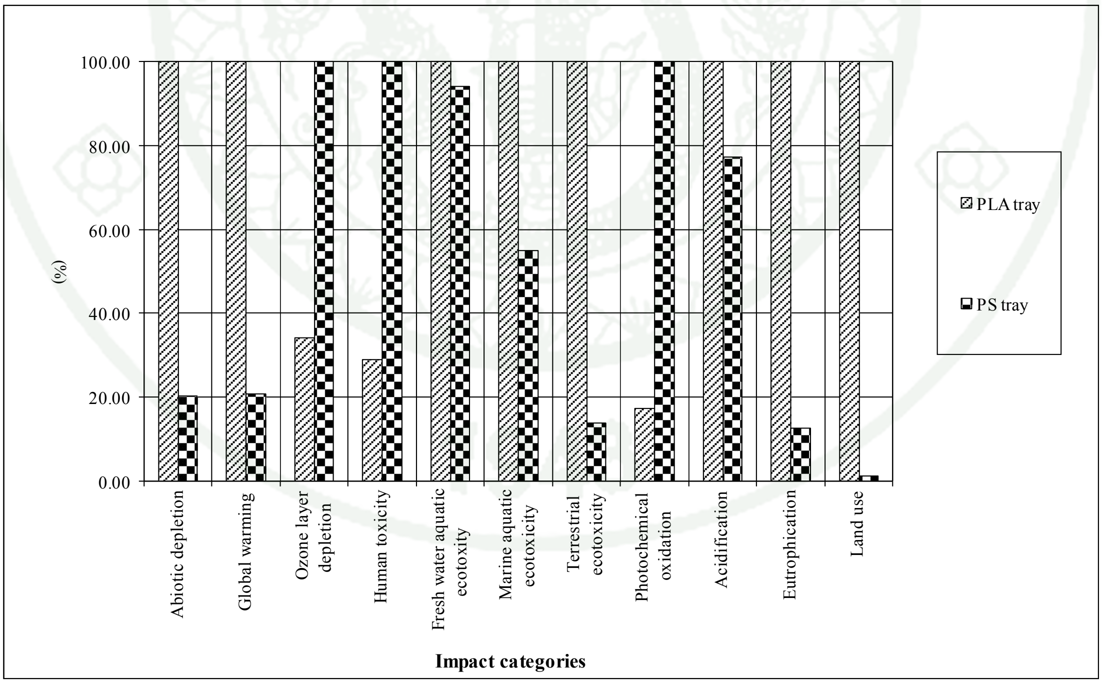


Figure 24 Comparison of the contribution of characterization value of each impact categories of PS and PLA trays (cradle-to-gate).

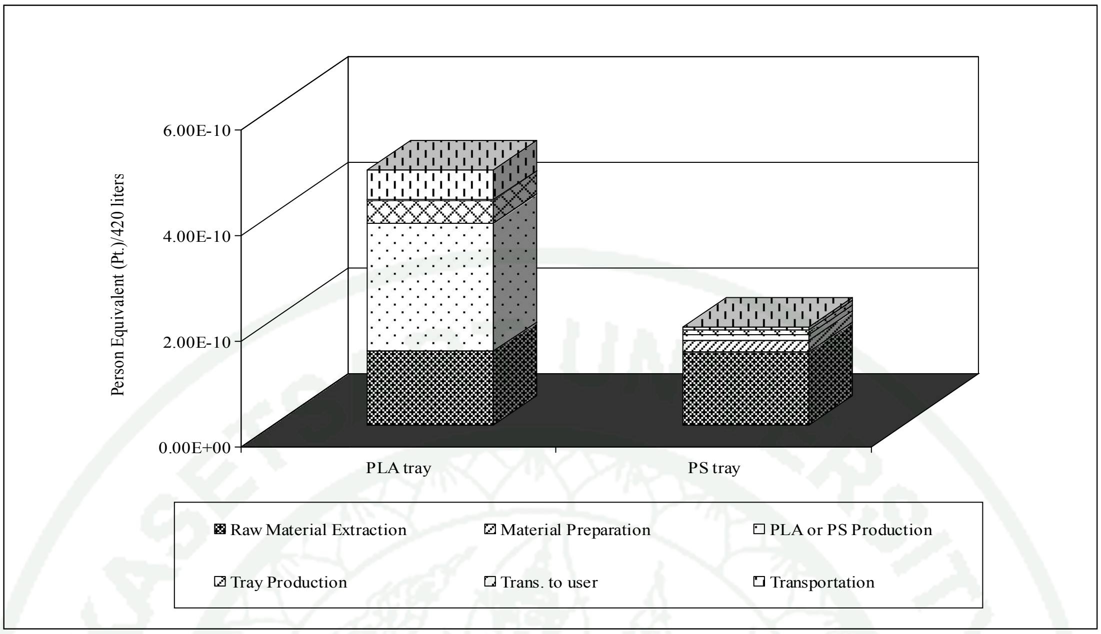


Figure 25 Comparison of total environmental impact scores of each phase of PS and PLA trays (cradle-to-gate).

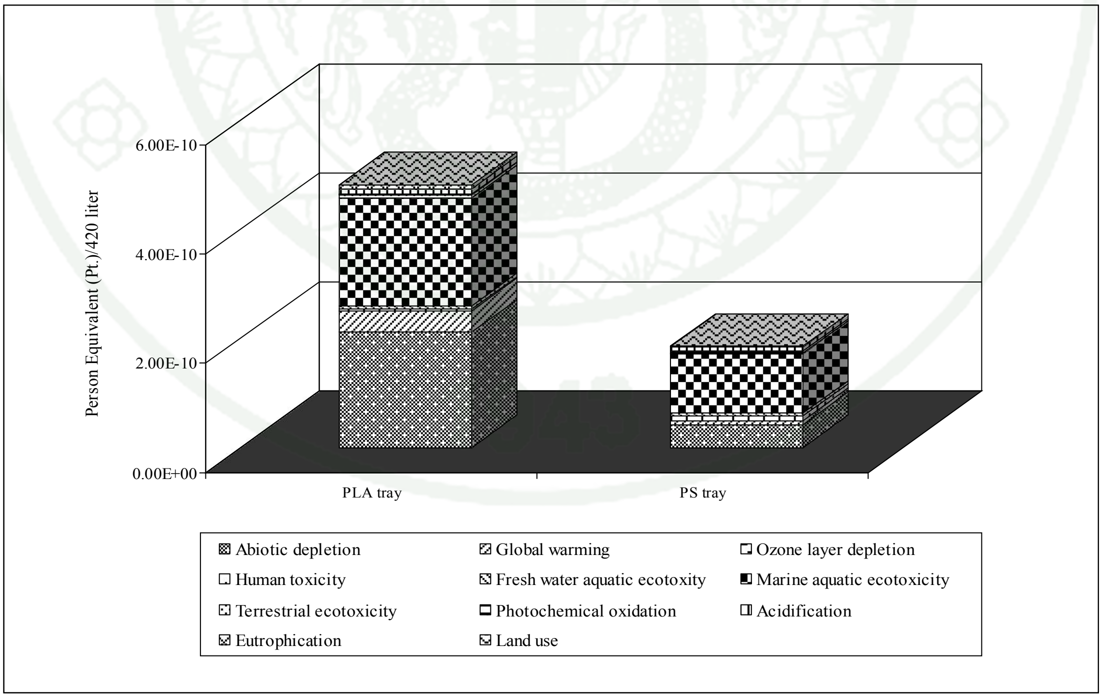


Figure 26 Comparison of total environmental impact scores in each impact categories of PLA and PS trays (cradle-to-gate).

1.6 Comparison of energy consumption through whole life cycle of PLA and PS trays

In a cradle to grave of LCA study, the results from the whole life cycle with end of life management are investigated. The results of life cycle energy consumption for two types of trays are shown in Figure 27.

It is found that PLA trays together with incineration with energy recovery (option 3) show the favorable option of 895.7 MJ/FU. The energy produced from incineration leads to preserve energy from the production of PLA trays by 20.3%, accounts for 241.51 MJ/FU. In addition, the PLA trays with option-5 (landfill with energy recovery from methane collection) or option-6 (composting) shows the good results. As mentioned above, energy from methane collection and the fertilizer products from composting treatment reduce the energy used by 10.2 % and 5.02%, which accounted 144.48 MJ/FU and 89.44 MJ/FU, respectively.

PS trays with incineration and heat recovery also show the best option. The reason is due to energy produced from incineration plants of 139.2 MJ/FU, which leads to 23.3 % energy preserve in the production of PS trays.

Incineration contributes the highest energy consumption for PLA and PS trays because high distance to incineration plant and high energy consumption to running incineration plant.

1.7 Comparison of environmental impacts through whole life cycle of PLA and PS trays

The impact assessment of the entire life cycle can be applied by considering all unit processes including production and disposal (cradle-to-grave). The characterization value in a cradle to grave of LCA study for two types of trays, the results of life cycle environmental impacts through whole life cycle of PLA and

PS trays are shown in Table 21 and Table 22, respectively. It is found that all impact categories, PLA trays have the environmental loads higher than those PS trays.

The assessment results show that the environment impact of production of PLA trays generate the highest environmental impact potentials, as shown in Figure 28 and Figure 29. Similarly, the comparison of the final weighted score for through the whole life cycle of PS and PLA trays is shown in Figure 28 and Figure 29. It can observe that the scores for PLA trays are approximately 51-57% higher than PS trays. This is due to the heavier weight of PLA trays and high energy consumption from PLA production. For PLA trays, the main causes of impact obtain from high amount of abiotic depletion, global warming, and marine aquatic ecotoxicity. Besides, disposal of composting for PLA trays reveals the highest contribution for terrestrial ecotoxicity.

The result shows that PLA trays with composting (option-5) is the best option of 4.93E-10 Pt./FU because carbon sequestration and fertilizer (N-P-K) products reduce the environmental impact by 13.4%, accounts for 7.65E-11 Pt./FU. Landfill with energy recovery from methane collection (option-5) is suitable with management of PLA trays, which reduce the environmental impact by 5.4%, accounts for 3.07E-11 Pt./FU. The following option, it is found that PLA trays together with incineration with energy recovery (option 3) also show the favorable option. The energy produced from incineration leads to reduce energy from the production of PLA trays by 3.2%, accounts for 1.85E-11 Pt./FU.

It is found that the worst scenario for PLA trays is option 1, where plastics waste is disposed of in landfill of 90% and incineration of 10%. The main causes come from high amount of landfill gas emission of PLA and high amount of combustion emission from incineration for PLA. PLA is disposed by landfill that contributes the second highest total environmental impact. The main environment total loads are mostly from global warming impact for both option-1 (landfill of 90% and incineration of 10%) and option-4 (landfill). It can be observed that PLA trays with option 1 have a higher environmental impact than those PLA trays with option 7.

This can have a considerable impact on the results due to the relatively strong greenhouse gas effect of CH_4.

Disposal of PS trays by incineration and heat recovery also shows the best option, which can reduce environment impact by 6.8%, accounts for 1.30E-11 Pt./FU. Whereas, disposal of PS trays by incineration of (option 2) generates the highest environmental impact. The second largest impacts are disposed by incineration, followed by landfill of 50% and incineration of 50% (option 7). The main causes come from high amount of combustion emission from incineration for PS. The main environmental loads are mostly from marine aquatic ecotoxicity, global warming, and abiotic depletion.

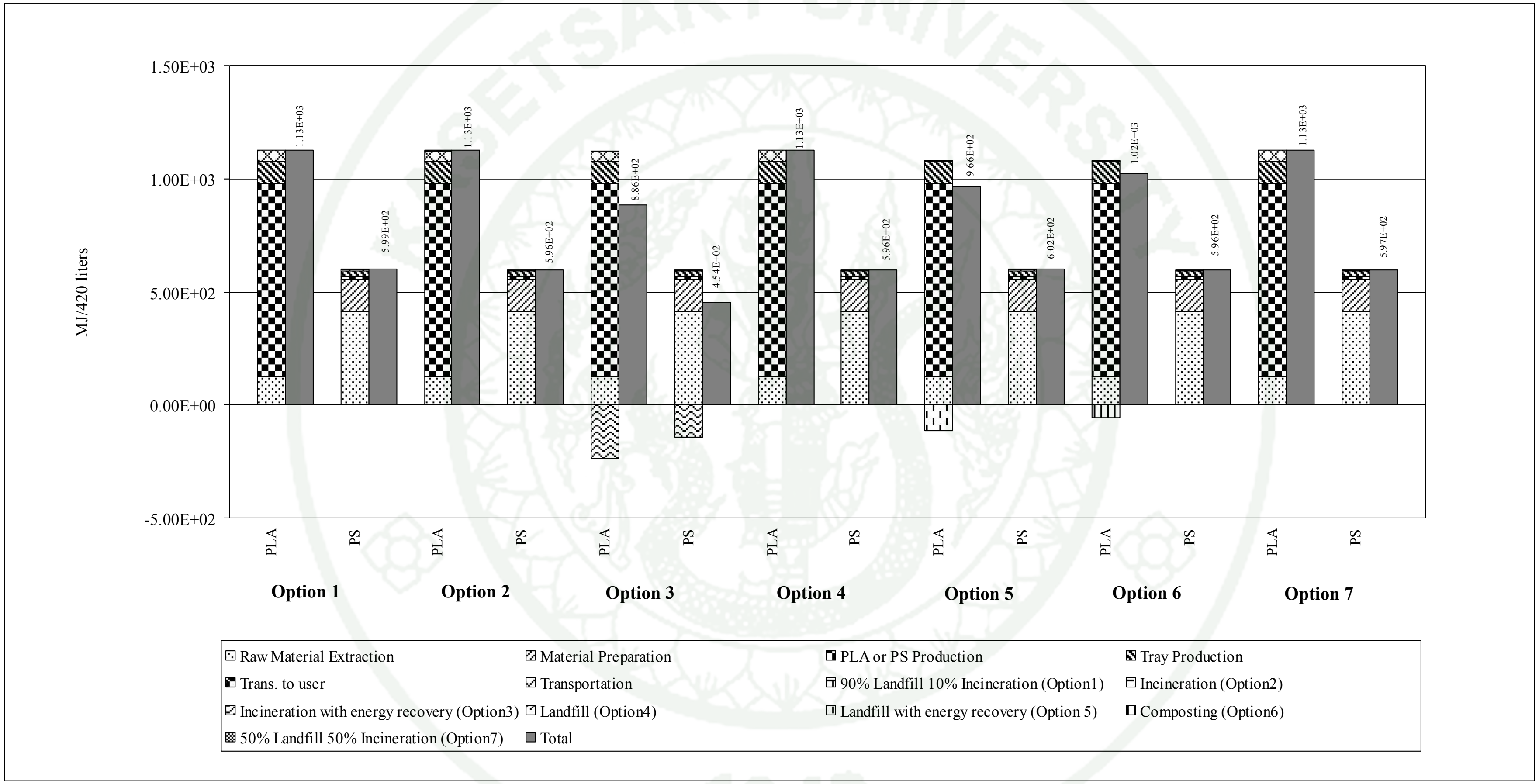


Figure 27 Comparison of energy consumption in each phase through life cycle of PLA and PS trays (cradle-to-grave).

Table 21 Environmental impact (Characterization value) through whole life cycle per functional unit of PLA trays (cradle-to-grave).

PLA + MSW options / Impact categories	Option-1: 90% landfill, 10% incineration	Option-2: Incineration	Option-3: Incineration-energy recovery	Option-4: Landfill	Option-5 Landfill-energy recovery	Option-6: Composting	Option-7: 50% landfill, 50% incineration	Unit
Abiotic depletion	1.52E+00	1.53E+00	1.49E+00	1.52E+00	1.27E+00	1.48E+00	1.52E+00	kg Sb eq
Global warming	2.73E+02	1.47E+02	1.29E+02	2.88E+02	1.42E+02	-5.53E+01	2.17E+02	kg CO2 eq
Ozone layer depletion	1.08E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	1.03E-05	1.08E-05	kg CFC-11eq
Human toxicity	1.65E+01	1.66E+01	1.54E+01	1.65E+01	1.64E+01	1.42E+01	1.65E+01	kg 1,4-DB eq
Fresh water aquatic	2.44E+00	2.48E+00	2.14E+00	2.44E+00	2.44E+00	4.74E+00	2.44E+00	kg 1,4-DB eq
Marine aquatic	1.75E+04	1.76E+04	1.64E+04	1.75E+04	1.75E+04	1.45E+04	1.75E+04	kg 1,4-DB eq
Terrestrial ecotoxicity	1.38E-01	1.39E-01	1.24E-01	1.38E-01	1.37E-01	1.18E+00	1.38E-01	kg 1,4-DB eq
Photochemical oxid.	5.32E-02	1.82E-02	1.68E-02	5.71E-02	2.44E-02	-2.84E-02	3.76E-02	kg C2H4
Acidification	7.30E-01	7.34E-01	6.94E-01	7.30E-01	6.85E-01	6.89E-01	7.30E-01	kg SO2 eq
Eutrophication	2.39E-01	2.40E-01	2.34E-01	2.39E-01	2.31E-01	2.05E-01	2.39E-01	kg PO4 eq
Land use	7.87E+00	1.42E+01	1.42E+01	7.17E+00	7.17E+00	2.37E+01	1.07E+01	m2yr

Table 22 Environmental impact (Characterization value) through whole life cycle per functional unit of PS trays (cradle-to-grave).

PS + MSW options / Impact categories	Option-1: 90% landfill, 10% incineration	Option-2: Incineration	Option-3: Incineration-energy recovery	Option-4: Landfill	Option-5 Landfill-energy recovery	Option-6: Composting	Option-7: 50% landfill, 50% incineration	Unit
Abiotic depletion	2.57E-01	2.62E-01	2.39E-01	2.56E-01	2.95E-01	2.56E-01	2.57E-01	kg Sb eq
Global warming	1.89E+01	2.98E+01	1.95E+01	1.90E+01	1.81E+01	1.74E+01	2.41E+01	kg CO2 eq
Ozone layer depletion	1.56E-05	1.56E-05	1.56E-05	1.55E-05	1.56E-05	1.55E-05	1.55E-05	kg CFC-11eq
Human toxicity	4.41E+01	4.42E+01	4.34E+01	4.41E+01	4.44E+01	4.46E+01	4.41E+01	kg 1,4-DB eq
Fresh water aquatic	2.38E+00	2.40E+00	2.20E+00	2.38E+00	2.39E+00	3.68E+00	2.37E+00	kg 1,4-DB eq
Marine aquatic	8.67E+03	8.74E+03	8.01E+03	8.66E+03	9.05E+03	8.92E+03	8.66E+03	kg 1,4-DB eq
Terrestrial ecotoxicity	2.08E-02	1.78E-02	8.90E-03	2.12E-02	2.14E-02	9.37E-01	1.89E-02	kg 1,4-DB eq
Photochemical oxid.	8.04E-02	8.01E-02	7.93E-02	8.04E-02	8.02E-02	8.00E-02	8.02E-02	kg C2H4
Acidification	4.02E-01	4.05E-01	3.82E-01	4.02E-01	4.04E-01	4.02E-01	4.02E-01	kg SO2 eq
Eutrophication	2.46E-02	2.53E-02	2.17E-02	2.45E-02	2.49E-02	2.45E-02	2.46E-02	kg PO4 eq
Land use	2.52E+01	7.10E+00	7.10E+00	2.72E+01	2.72E+01	2.66E+01	1.72E+01	m2yr

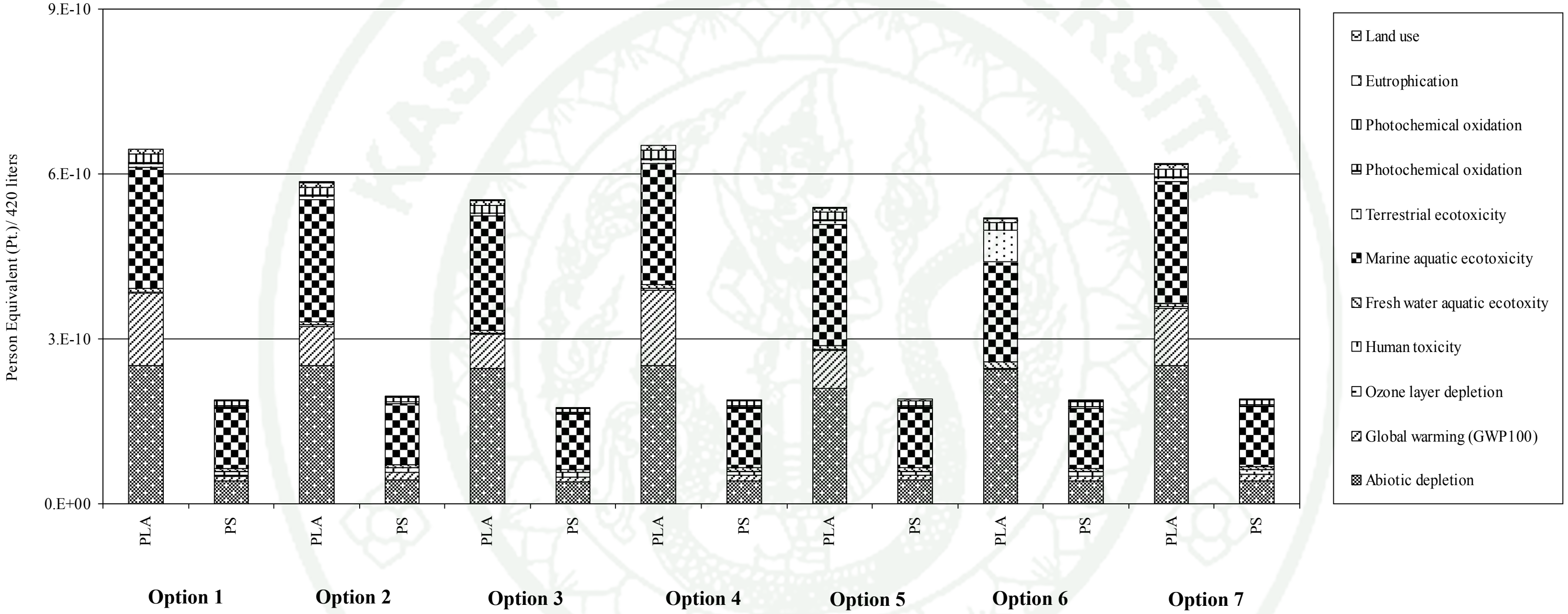


Figure 28 Comparison of the total environmental impacts through whole life cycle per functional unit of PLA and PS trays (cradle-to-grave).

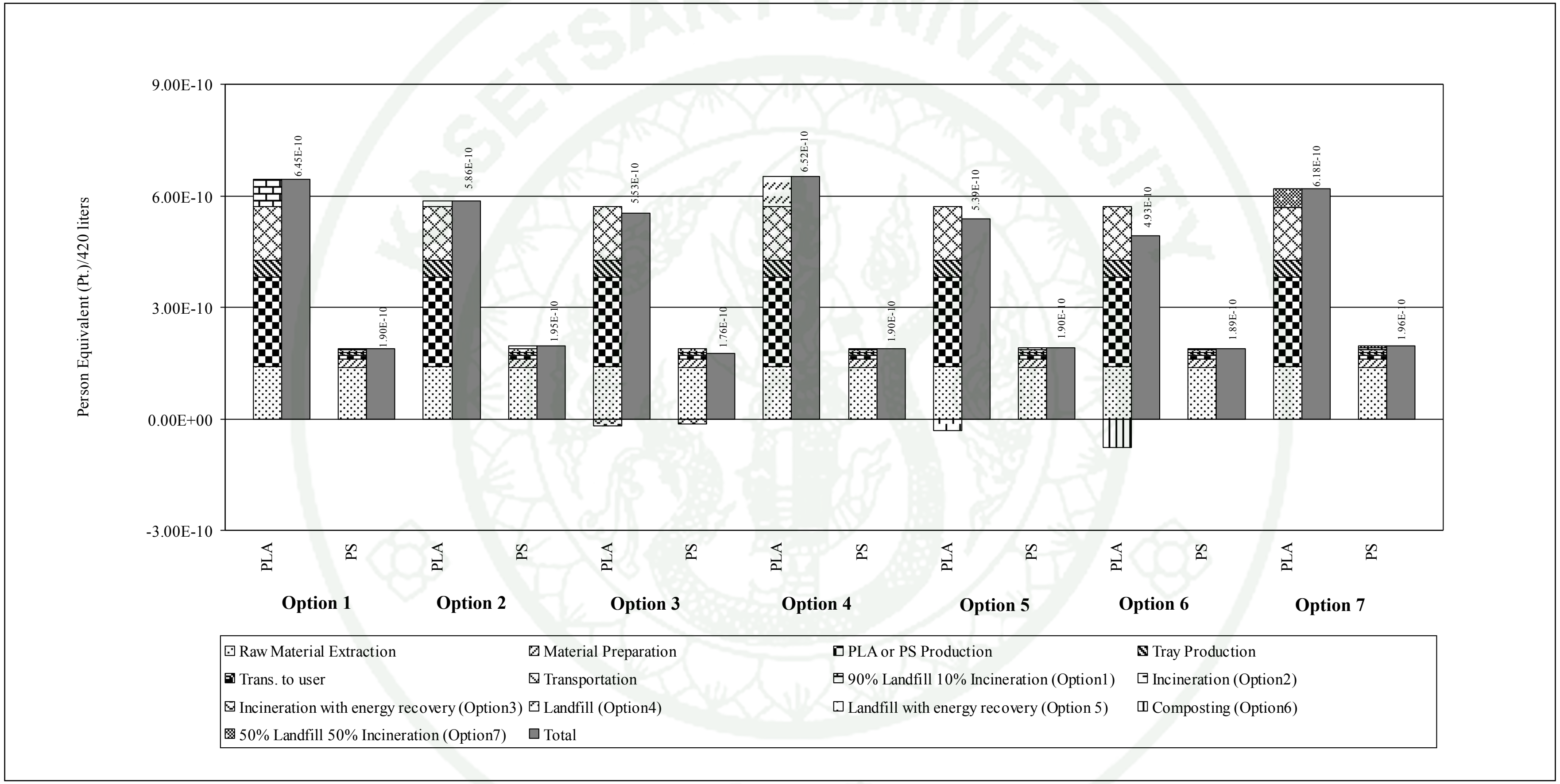


Figure 29 Comparison of the total environmental impacts score of each process through whole life cycle per functional unit of PLA and PS tray (cradle-to-grave).

1.8 Improvement

In this section, hypothesis for the improvements of the process based on the results obtains from LCA study. Detailed information of improvement scenarios for each plastic are described as follows.

1.8.1 PLA trays with process improvement (PLA-improved)

From the previous results, the energy consumption and environmental impact of the production of the PLA trays are mainly from natural gas and electricity consumption and heavier weight of PLA trays. In the next LCA study, the following improvement scenarios for PLA are compared:

1) Using racycle PLA pellets in tray manufacturing, (PLA-improved 1).

2) Using PLA pellets production in Thailand (Raying province), (PLA-improved 2).

3) Reducing the amount of materials usage in tray manufacturing of 10% (Tan and Khoo, 2005), (PLA-improved 3).

4) Reducing the amount of materials usage in forming process of 50% (PLA-improved 4).

5) Using biomass feedstock for PLA pellets production (Vink *et al.,* 2003) (PLA-improved 5).

6) The improvement of hypothetical PLA improved includes using recycle PLA pellets in tray manufacturing, reducing the amount of materials

usage in tray manufacturing of 10%, using biomass feedstock for PLA pellets production, (PLA-improved 6).

7) The improvement of hypothetical PLA-improved includes using recycle PLA pellets in tray manufacturing, reducing the amount of materials usage in tray manufacturing of 50%, using biomass feedstock for PLA pellets production, (PLA-improved 7).

1.8.2 LCI data of PLA trays with process improvement

The detail of input-output data in each case of PLA-improved are summarized as follows:

Firstly, the LCI data of PLA trays with recycling pellets in tray manufacturing are shown in Appendix Table B3. Details information of tray manufacturing with recycling process is shown in Figure 30.

Second, since PLA pellets production plant is located in Thailand (Rayong province), the LCI of transportation phase PLA trays is shown in Appendix Table B 4. Distance for transportation was calculated based on average distance of corn plantation to PLA production in Thailand. Normal average and production average of distance for corn plantation to PLA production are summarized in Appendix Table B5.

Third, since the amount of materials usage in tray manufacturing of are reduced of 10% or 50%, the LCI of tray manufacturing phase of PLA trays is shown in Appendix Table B6. Details information is shown in Figure 31.

Fourth, since using biomass feedstock for PLA pellets production (Vink *et al.,* 2003), the LCI of tray manufacturing phase of PLA trays are summarized in Appendix Table B7.

Finally, the improvement of hypothetical PLA trays includes using recycle PLA pellets in tray manufacturing, using PLA pellets production in Thailand (Rayong province), using biomass feedstock for PLA pellets production (Vink *et al.,* 2003), and reducing the amount of materials usage in tray manufacturing of 10% or 50%. The results of LCI data for PLA-improved 6 or PLA-improved can be used information from Appendix Table B 3, Table B 4, Table B 5, Table B6, and Table B7.

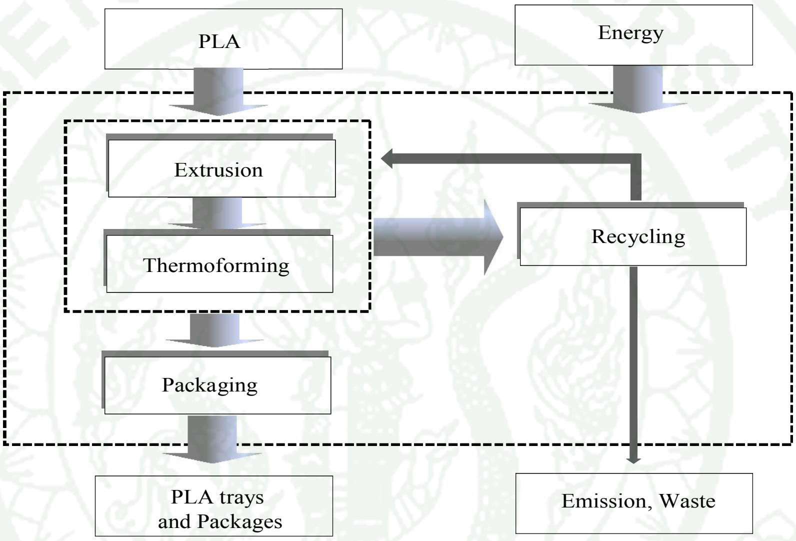


Figure 30 Input-output of trays production with recycling process.

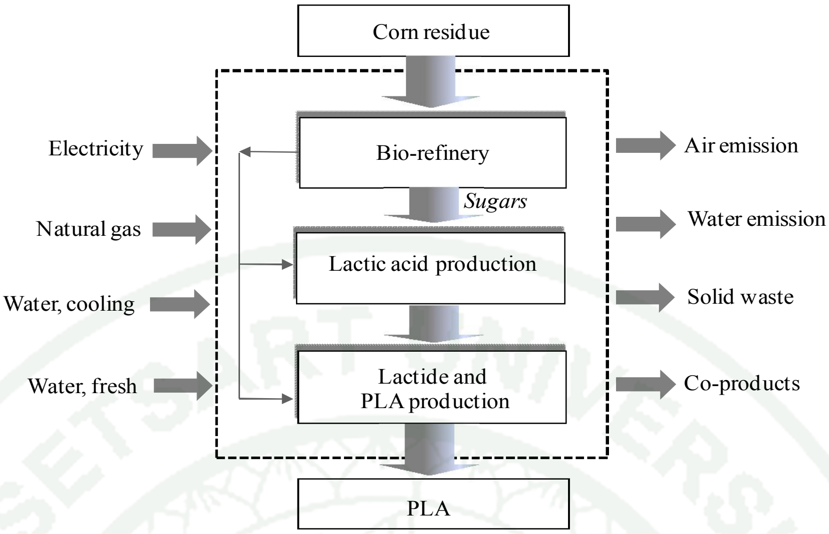


Figure 31 Input-output of PLA production with biomass feedstock.

Source: Vink *et al.* (2003).

1.8.3 Energy consumption of PLA trays with process improvement (PLA-improved)

The comparison of energy consumption of PLA trays and PLA – improved are presented in Figure 30. Major cause of lower energy consumption in each case PLA-improved are summarized as follows:

Firstly, using recycling PLA pellets in tray manufacturing leads to saving energy consumption of 129.8 MJ which is 11.5 % lower than that of the PLA-baseline. Second, since PLA pellets production plant is located in Thailand, less transportation distance reduce fossil energy consumption of 25.4 MJ resulted in reduction of energy from the base case by 2.3%. Third, the following improvement reduces material consumption by 10% or 50% lead to saving energy consumption of 102.4 MJ and 512.0 MJ which is 9.1 % and 45.5% respectively lower than that of the PLA-baseline. Fourth, using biomass feedstock for PLA pellets production (Vink *et al.,* 2003) reduce fossil energy consumption of 516.6 MJ resulted in reduction of energy from the base case by 45.9%. As above results, the energy used for the PLA-improved 5 is slightly lower than PS trays by 9 %.

Finally, the improvement of hypothetical PLA trays includes using recycle PLA pellets in tray manufacturing, using PLA pellets production in Thailand (Raying province), using biomass feedstock for PLA pellets production (Vink *et al.,* 2003), and reducing the amount of materials usage in tray manufacturing of 10% . Therefore, PLA- improved 6 has 52.2% lower energy consumption than the PLA-baseline. Additionally, the energy used for the PLA- improved 6 is lower than PS trays by 19 %, which is mainly due to energy consumption in PLA pellets production. While, PLA- improved 7 has 15.1% lower energy consumption than the PLA- improved 6 because less material consumption for PLA trays of 50%.

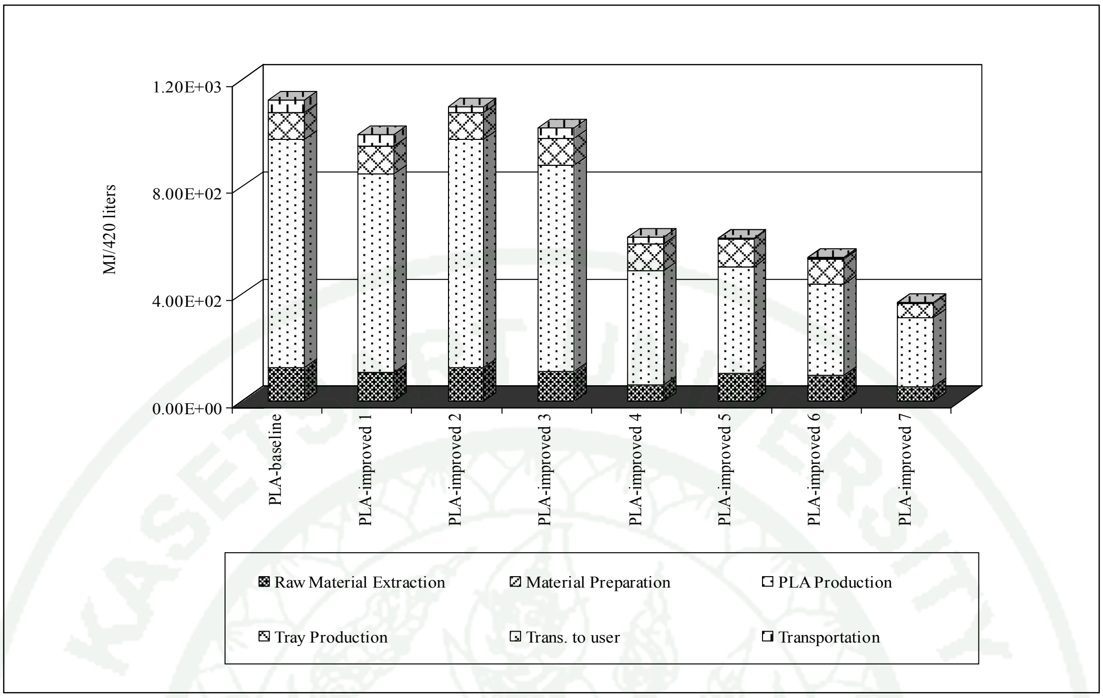


Figure 32 Comparison of the contribution of energy consumption in each phase of PLA-baseline and PLA-improved (cradle-to-gate).

1.8.4 Environmental impact of PLA trays with process improvement (PLA-improved).

Figure 31 shows the comparison of environmental impact potentials of all impact categories, which are grouped into the single score or the total environmental impact.

It is found that the total environmental impact of PLA-baseline is higher that PLA-improved of 1.1-2.2 times. Major cause of impact of PLA-improved also comes from abiotic depletion and marine aquatic ecotoxicity, and global warming, which accounts for 92.4% – 93.8%. The environmental impact potentials of each phase in the whole life cycle of PLA-improved, the main load comes from corn cultivation and PLA production, which is 51.23 and 39.04 %, respectively, as shown in Figure 32.

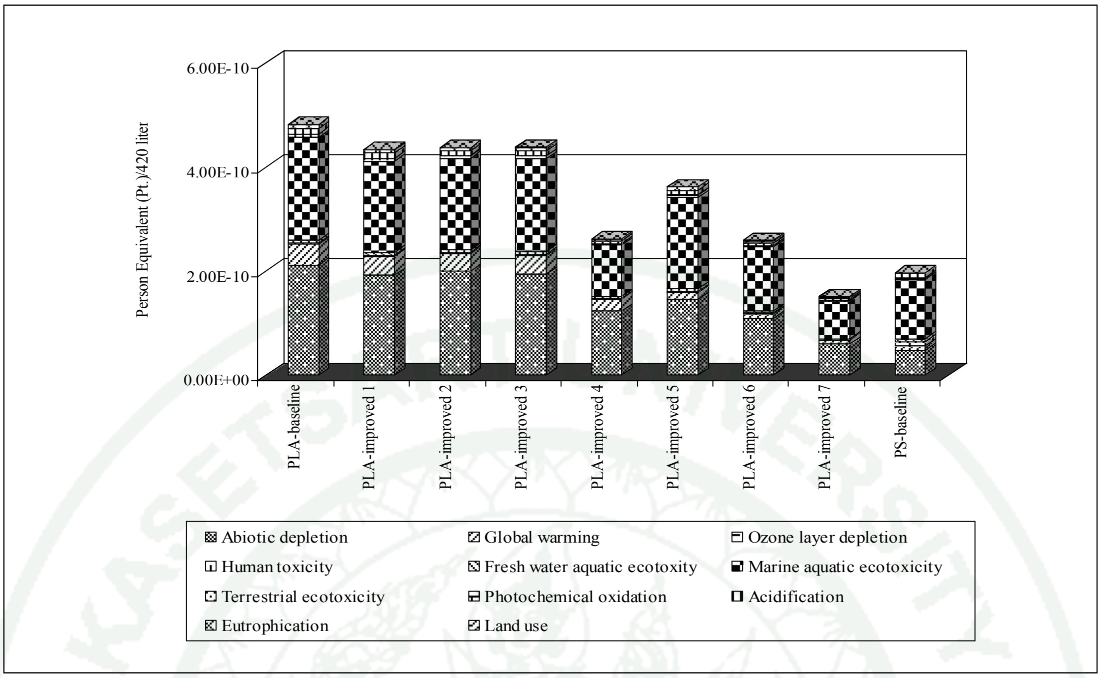


Figure 33 Comparison of total environmental impact scores of PLA-baseline and PLA improved (cradle-to-gate).

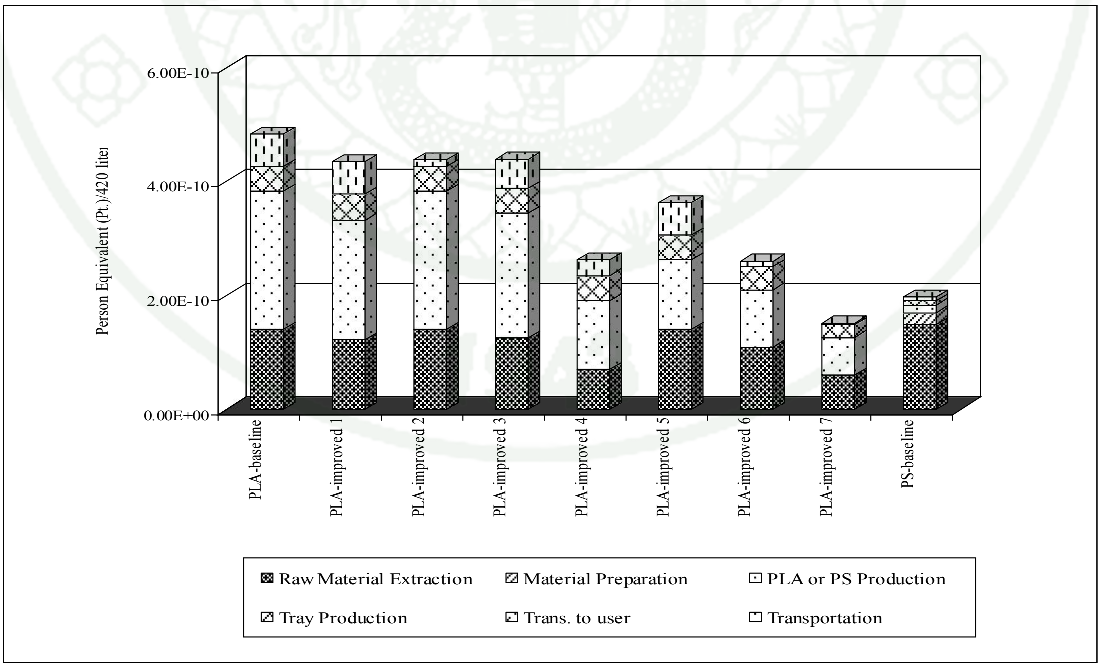


Figure 34 Comparison of total environmental impact scores in each phase of PLA-baseline and PLA- improved (cradle-to-gate).

1.8.5 PS trays with process improvement (PS-improved)

From the previous results, the energy consumption and environmental impact of the production of the PS tray (PS-baseline) are mainly from raw material extraction. In the next LCA study, the following improvement scenarios for PS are described as follows:

1) Using racycle PS pellets in tray manufacturing, (PLA-improved 1).

2) Reducing the amount of materials usage in tray manufacturing of 10% (Tan and Khoo, 2005), (PS-improved 2).

3) Reducing the amount of materials usage in tray manufacturing 50% (PLA-improved 3).

4) The improvement of hypothetical PS improved includes using recycling PS pellets in tray manufacturing, reducing the amount of materials usage in tray manufacturing of 10%, (PS-improved 4).

5) The improvement of hypothetical PS improved includes using recycling PS pellets in tray manufacturing, reducing the amount of materials usage in tray manufacturing of 10%, (PS-improved 5).

1.8.6 Energy consumption of PS trays with process improvement (PS-improved)

The comparison of energy consumption of PS trays and PS – improved is presented in Figure 35. Major cause of lower energy consumption in each case PLA-improved are summarized as follows:

Firstly, using recycle PS pellets in tray manufacturing leads to saving energy consumption of 249.6 MJ which is 37.4 % lower than that of from the PS-baseline. Second, the following improvement reduces material consumption by 10% or 50% lead to saving energy consumption of 69.1 MJ and 334.6 MJ respectively lower than that of from the PS-baseline.

Finally, the improvement of hypothetical PS trays includes using recycle PS pellets in tray manufacturing, and reducing the amount of materials usage in tray manufacturing of 10%. Therefore, PS- improved 4 has 42.7% lower energy consumption than the PS-baseline. While, PS- improved 5 has 23.1% lower energy consumption than the PLA- improved 4 because less material consumption for PS trays of 50%.

1.8.7 Environmental impact of PS trays with process improvement (PS-improved)

Figure 36 shows the comparison of environmental impact potentials of all impact categories, which are grouped into the single score or the total environmental impact. It is found that the total environmental impact of PS-baseline is higher that PS-improved of 1.1-2.2 times. Major cause of impact of PS-improved also comes from abiotic depletion and marine aquatic ecotoxicity, and global warming, which accounts for 83.64%. The environmental impact potentials of each phase in the whole life cycle of PS-improved, the main load comes from raw material extraction and tray production, which is 65.02 and 16.62 %, respectively, as shown in Figure 37.

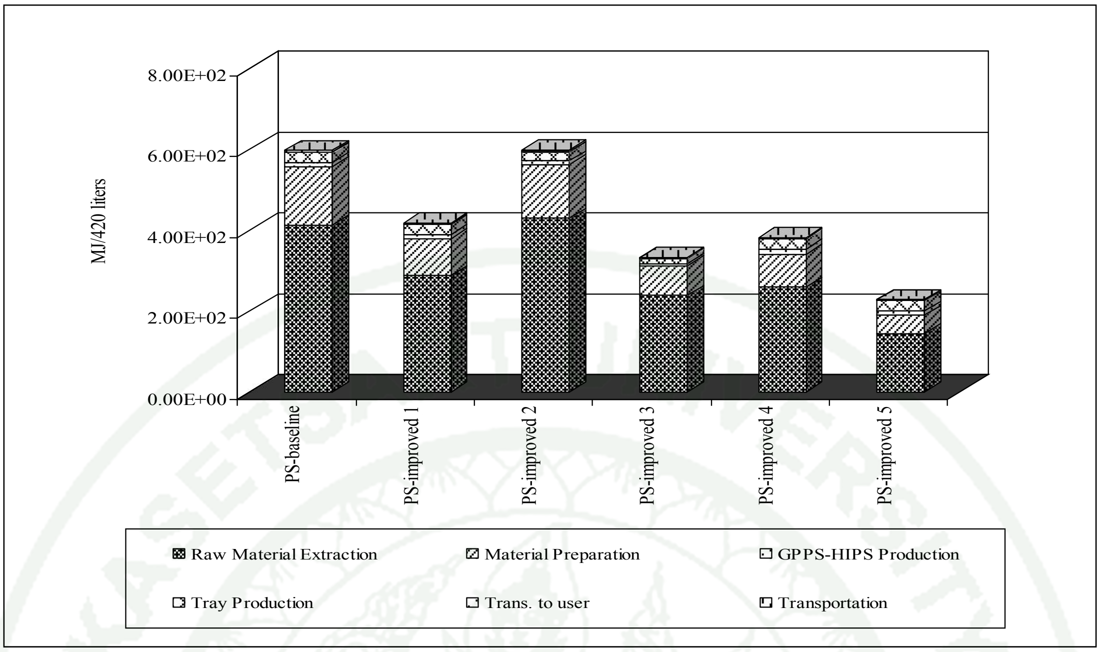


Figure 35 Comparison of the contribution of energy consumption in each phase of PS-baseline and PS-improved (cradle-to-gate).

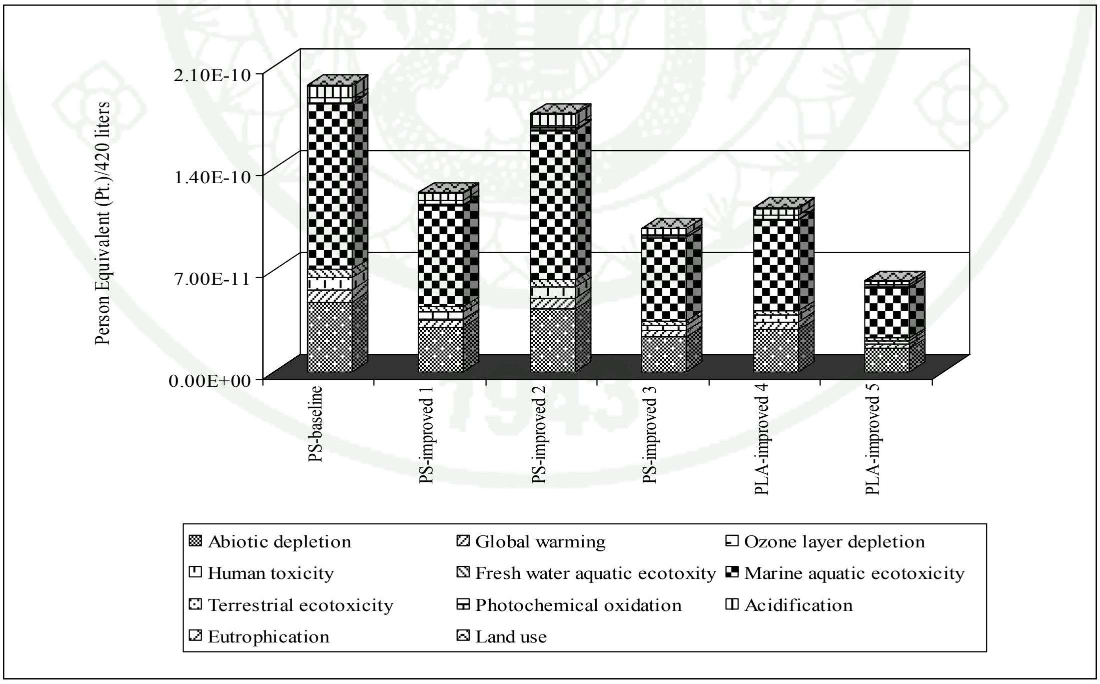


Figure 36 Comparison of total environmental impact scores of PS-baseline and PS-improved (cradle-to-gate).

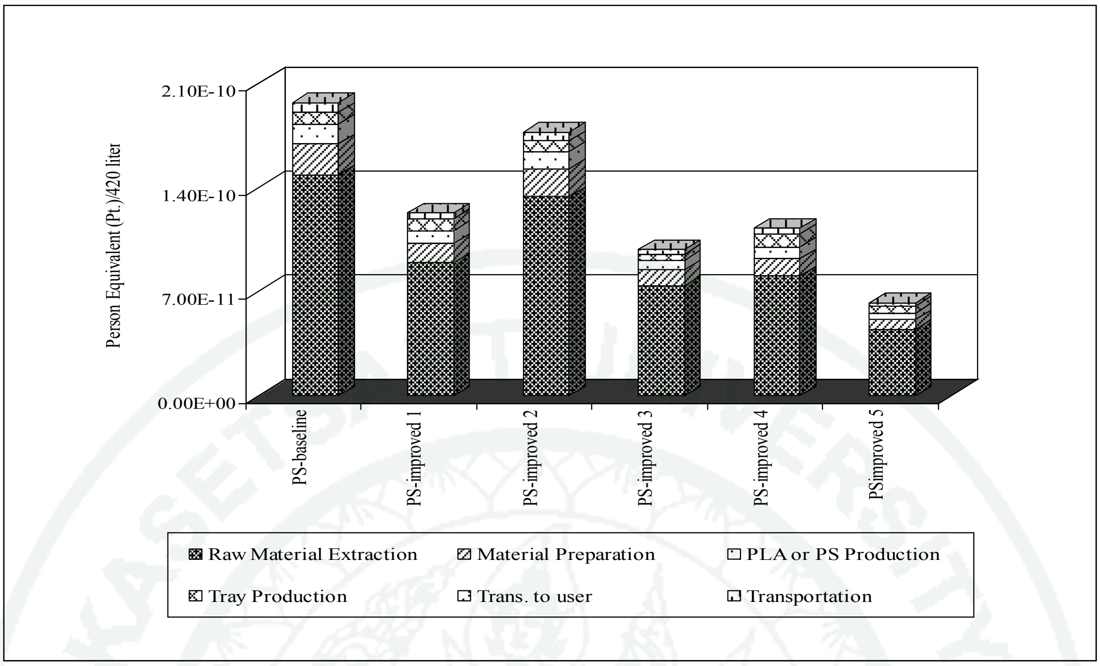


Figure 37 Comparison of total environmental impact scores of each phase of PS-baseline and PS- improved (cradle-to-gate).

1.9 The comparison to the other studies (cradle-to-gate)

The comparison of the energy consumption and GHG emissions per kg of HIPS, GPPS, PLA pellets, and biomass feedstock for PLA pellets production are within the range of the data from obtained other sources, as shown in Table 23 and Table 24, respectively.

The comparison of the energy consumption per kg PS pellets, the energy used per kg of HIPS is quite higher than GPPS caused by usage polybutadiene rubber of 0.12 kg, which consume energy of 10.8 MJ. Additionally, the comparisons of the GHG emissions per kg of both PLA pellets are consistent with the value in Vink *et al.* (2003) and Bohlmann (2003).

Table 23 Comparison of energy consumption of HIPS, GPPS, and PLA pellets with the other studies (Unit: MJ/kg).

	This study	SimaPro 7 (2008)	PlasticsEU (2008)	Hisun Co.,Ltd (2006)	Bohlmann (2003)	Vink *et al.* (2003)
HIPS	96.53	101.00	87.20	_	_	_
GPPS	85.72	86.70	87.20	_	_	_
PLA	55.19	_	_	64.13	51.00	54.10
PLA*	33.31	_	_	_	_	29.2

* PLA is using biomass feedstock for PLA pellets production

Table 24 Comparison of the GHG emission of HIPS, GPPS, and PLA pellets with the other studies (Unit: kg CO_2 eq./kg).

	This study	SimaPro 7 (2008)	PlasticsEU (2008)	Hisun Co.,Ltd (2006)	Bohlmann (2003)	Vink *et al.* (2003)
HIPS	2.65	3.05	3.46	_	_	_
GPPS	2.25	2.66	3.46	_	_	_
PLA	2.98	_	_	1.62	2.71	1.8
PLA*	0.34	_	_	_	_	-0.3

* PLA is using biomass feedstock for PLA pellets production

1.10 Carbon footprint

The comparison of life cycle GHG emissions (carbon footprint) is shown in Figure 36. For the first part of this study, the production of PS trays and PLA trays were considered.

The results of GHG emission for each type of tray are shown in Figure 36. The highest GHG emission from PLA trays come from PLA pellets production which is 4.94 times higher than that PS tray. Besides, it can be observe that the higher weight of PLA trays (15.10 grams/tray) mentions above results. For PLA trays, PLA pellets production generates 86.82% 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 a relative high proportion to decrease total GHG emissions for PLA-baseline of 37.98%. The results of GHG emission for PS tray, the raw materials preparation, crude oil and natural gas extraction are the main effect to the GHG emissions in the PS tray, which accounts for 71.81%. Additionally, the proportionally high usage of GPPS up to 93.5% in the tray forming step together with the fewer raw materials used of 4.03 grams/tray could greatly reduce GHG emissions.

In the second part, the different waste management scenarios of PS trays, PLA trays were considered. The result shows that PLA trays with composting is the best option of -53.3 kg CO_2 equivalent/FU because of carbon sequestration and fertilizer (N-P-K) products. It leads to GHG reduction of 175.17 kg CO_2 equivalent/FU. In addition, PLA trays with landfill with energy recovery from methane collection and PLA trays with incineration and heat recovery also shows a good result as it contributes GHG reduction of 18.0 kg CO_2 equivalent/FU and 17.17 kg CO_2 equivalent/FU, respectively.

The GHG emissions obtained from the electricity generated using fossil fuels can be replaced those obtained from the electricity generation from the landfill with energy recovery from methane collection. Accordingly, the negative values of GHG reduction are shown in Figure 38.

The experiment results, composting and landfill are not suitable MSW options for PS tray because it is not is not decomposed. Whereas, PS trays with incineration and heat recovery shows the favorable option due to the capture of GHG emissions from incineration plant, which is 10.27 kg CO_2 equivalent/FU.

Scenario 7 (landfill of 90% and incineration of 10%) and the current scenario 1 (landfill of 90% and incineration of 10%) show the high GHG emission for both PLA and PS. However, in this scenario, it can be observe that an increase in incineration content increases the amount of GHG emissions for the two plastics due to combustion emission from incineration. The worst scenarios of life cycle GHG emissions for PLA and PS is disposed of in landfill and incineration. The main causes come from high amount of landfill gas emission of PLA and high amount of combustion emission from incineration for PS, which accounts for 168 kg CO_2 equivalent/FU and 11.9 kg CO_2 equivalent/FU, respectively.

1.11 Sensitivity analysis

The sensitivity analyses were performed to determine the influence of a change in the inventory data on the results of the impact assessment.

The influence of CH_4 emission of disposed by landfill and landfill with energy recovery from methane collection at the ratio CH_4 and CO_4 of 50:50, 60:40, 70:30, 80:20, 90:10 , and 100:0 were considered. Figure 37 shows the total environmental impact of PLA trays with disposal by landfill. It is clearly observed that since the ratio CH_4 emissions in the landfill is higher than 50%, total environmental impact score of PLA trays is increased. As above results, the environmental impact potential of CH_4 emission is higher than 21 times of CO_2 emissions. Whereas, the total environmental impact score of PLA trays with disposal by landfill with energy recover from methane is decreased because CH_4 emissions in the landfill are recovered to energy (electricity or heat), as presented in Figure 38.

The influence of heavy metals of disposed by composting with based on heavy metals from plastics (option 6) and heavy metals from plastics together with inoculumns (option 6*). The total environmental impact score of both PLA and PS trays with disposal by composting (option 6*) are increased because high amount of heavy metals emission of inoculums resulting from agriculture waste, as presented in Figure 41.

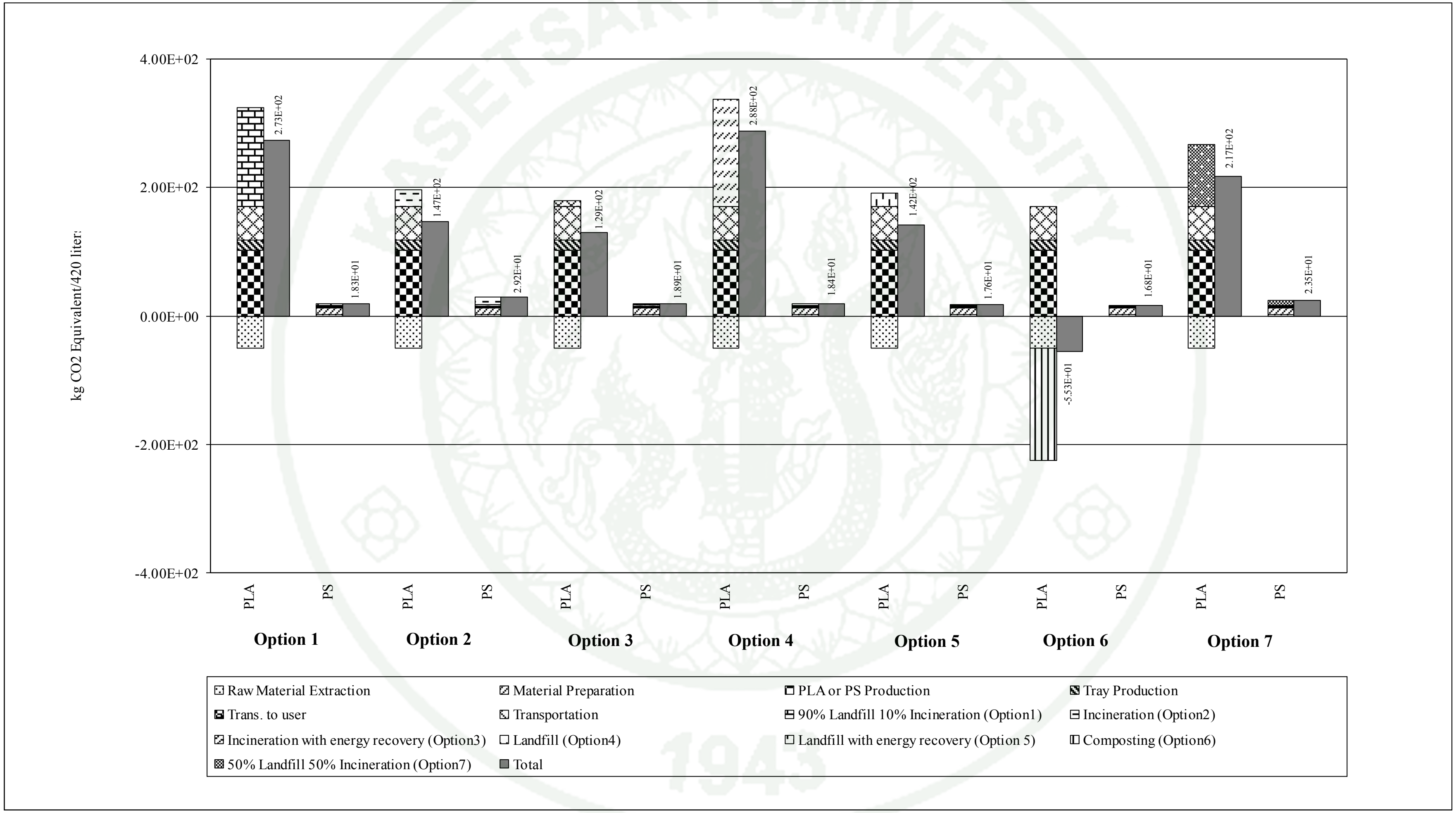


Figure 38 Comparison of GHG emission through life cycle of PLA and PS trays (cradle-to-grave).

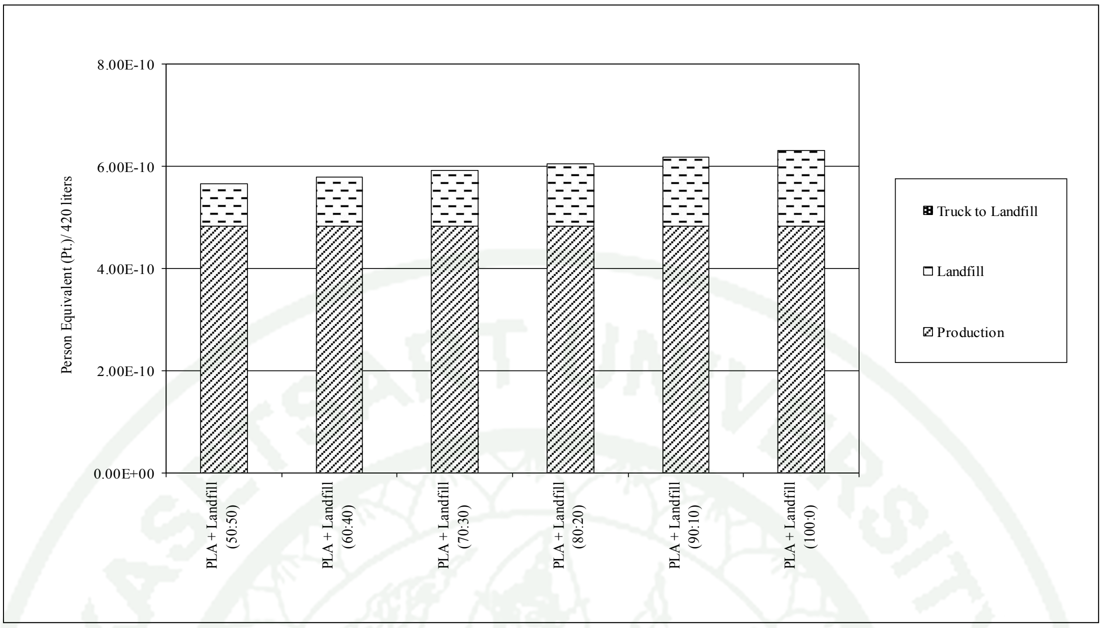


Figure 39 Sensitivity of the total environmental impact score through whole life of PLA trays with landfill with varying the ratio CO_2 and CH_4 emissions.

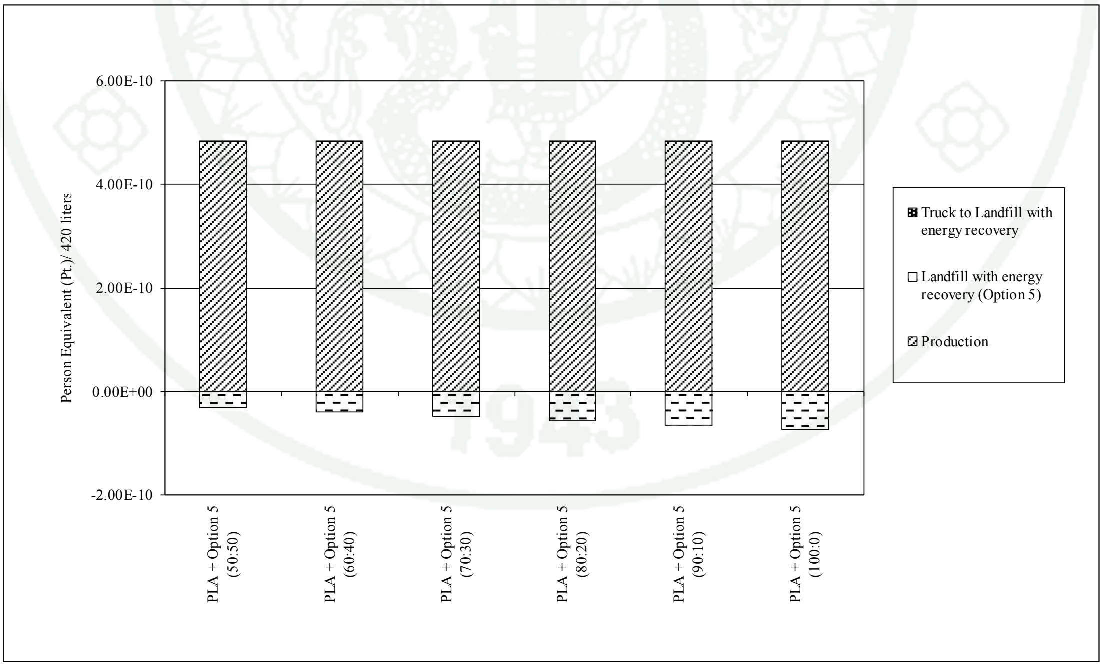


Figure 40 Comparison of sensitivity of the total environmental impact score through whole life of PLA-baseline with landfill and energy recovery with varying the ratio CO_2 and CH_4 emissions.

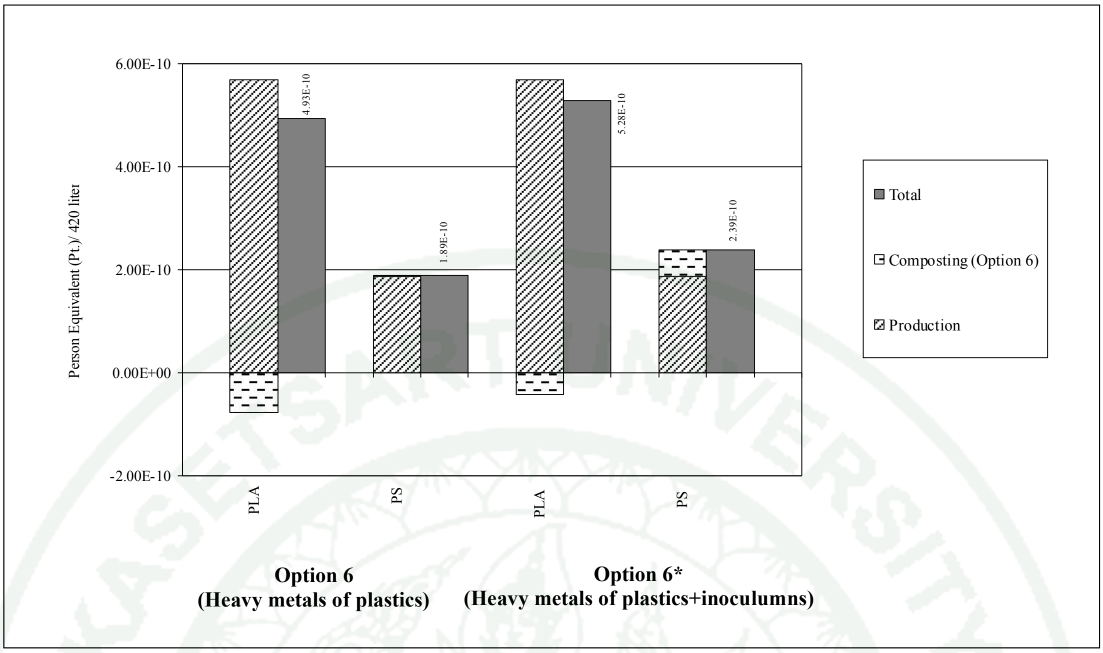


Figure 41 Comparison of sensitivity of the total environmental impact score through whole life of PLA-baseline with composting with based on heavy metals from plastics and heavy metals from plastics together with inoculumns.

2. LCI data and environmental impact of garbage bags

The LCI data from the production of garbage bag consists of six stage including raw materials extraction, raw materials preparation (ethylene), HDPE, LDPE and LLDPE production, garbage bag manufacturing, using, and transportation. Garbage bag production consists of five main steps including mixing, blowing and printing, cutting, recycling, and packaging. Plastic pellets and chemicals were mixed in the mixing machine, and shaped using extrusion blown film and printed using printing machine and then cut and packaged. Some factory using recycling pellets replaced virgin materials. Recycling process was used for give plastic pellets from plastics waste (scrap) which was discharged from forming steps. Figure 42 shows a typical process flow diagram of garbage bag production. Detailed information of LCI in each types of garbage bags are described as follows:

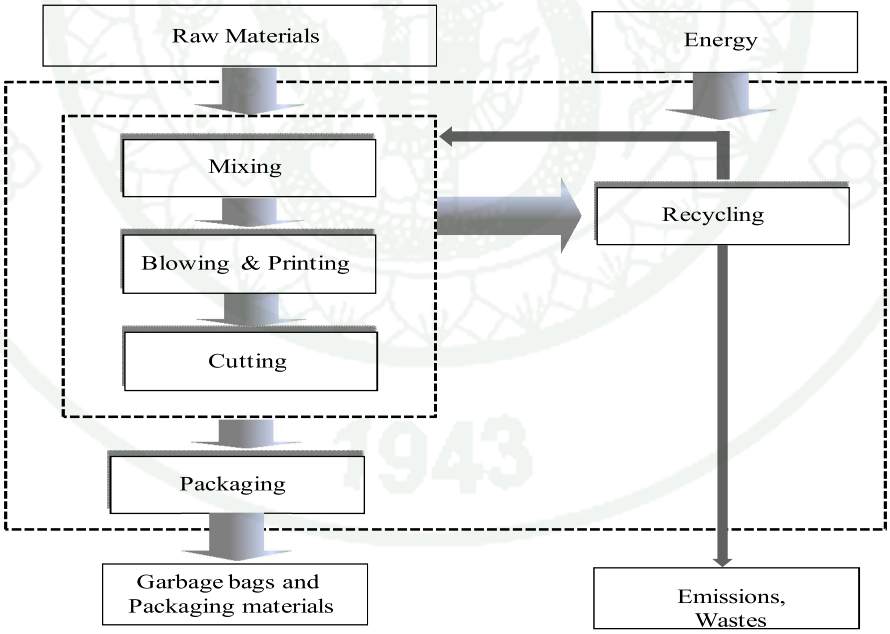


Figure 42 Typical process flow diagram of garbage bag production.

2.1 LCI data of garbage bags

2.1.1 LCI data of PE/starch garbage bags

The LCI data from the production of PE/starch garbage bag consist of six stage including raw material extraction (crude oil, natural gas, cassava plantation), raw materials preparation (ethylene), HDPE and LDPE production, PE/starch garbage bag manufacturing, using, and transportation. Detailed information of LCI in each process are described as follows:

1) Raw materials extraction

- Crude oil and natural gas exploration

Detailed information of crude oil exploration and natural gas extraction have already presented in Appendix Table C1 and Appendix Table C2.

- Cassava plantation

The LCI of cassava plantation was carried out by collecting the necessary information from Khongsiri (2009). This data of cassava plantation was collected from the Thai Tapioca Development Institute (Hauybong), Kasetsart University in Nakornratchasima province. Quantity of fuel and material input in cassava per 1,000 kg are summarized in Appendix Table D1.

2) Materials preparation

Ethylene was raw material for HDPE and LDPE which supplemented from SimaPro 7.0 database and National life cycle inventory database project (MTEC, 2009a), respectively. Data of this report collected from ethylene production 50% of total capacity production of Thailand. Information of main material for ethylene production was from naphtha and propane.

3) LDPE, HDPE and cassava starch production

Information of HDPE and LDPE production were also reviewed from SimaPro 7.0 database and National life cycle inventory database project (MTEC, 2009a), respectively. Data of this report collected from LDPE production 50% of total capacity production of Thailand.

The LCI of cassava starch production data was carried out by collecting the necessary information from Khongsiri (2009). This data of cassava cultivation was collected from 4 factories in the Thailand, which located in Nakornratchasima, Chonburi and Kalasin province. Detailed average inventory data of cassava starch per 1,000 kgs are summarized in Appendix Table D2.

4) PE/starch garbage bag production

Information of PE/starch garbage bag production was also reviewed National life cycle inventory database project (MTEC, 2009a). Data of this report collected from PE/starch garbage bag 50% of total capacity production of Thailand. PE/starch garbage bag production consists of 4 main step including mixing, blowing and printing, cutting, and excluding recycling process. PE/starch garbage bag employed process as presented in Figure 39 but excluding recycling process. The LDPE and HDPE pellets were raw materials for PE/starch garbage bags.

5) Using

The avoided energy used or waste generation during used for garbage bags. Therefore, the LCI result shows that garbage bags contribute a zero energy used and emissions. This study presumes that distance from garbage bags factory to user is completely 20 km.

6) Transportation

Detailed of raw material transportation in the entire life cycle of PE/starch garbage bags are as follows:

Information of crude oil and natural gas transportation are shown in Appendix Table C 5 and Appendix Table C6. Distance of material transportation for LDPE and HDPE production is shown in Appendix Table D3. This study presumes that distance from factory to factory is completely 2 km. Information of LDPE and HDPE pellets transportation were calculated based on average distance from Rayong province to garbage bag factory at Nakornpatom province in Thailand, as shown in Appendix Table D4. Information of cassava starch transportation were calculated based on average distance from starch factories to garbage bag factory at Nakornpatom province, as shown in Appendix Table D5.

2.1.2 LCI data of PE/TDPA garbage bags

The LCI data from the production of PE/TDPA garbage bag consist of six stage including raw materials extraction (crude oil and natural gas), raw materials preparation (ethylene), HDPE and LDPE production, garbage bag manufacturing, using, and transportation. Detailed information of LCI in each process are as follow:

1) Raw material extraction

- Crude oil and natural gas exploration

Detailed information of crude oil exploration and natural gas extraction have already presented in Appendix Table C1 and Appendix Table C2.

2) Material preparation

Ethylene was raw material for HDPE and LDPE, which supplemented from SimaPro 7.0 database and National life cycle inventory database project (MTEC, 2009a), respectively.

3) LDPE and HDPE production

Information of HDPE and LDPE production were also reviewed from SimaPro 7.0 database and National life cycle inventory database project (MTEC, 2009a), respectively.

4) PE/TDPA garbage bag production

Information of PE/TDPA garbage bag production was also reviewed National life cycle inventory database project (MTEC, 2009a). Data of this report collected from PE/ TDPA garbage bag 50% of total capacity production of Thailand. PE/TDPA garbage bag production consists of 5 main steps including mixing, blowing and printing, cutting, and recycling process. PE/TDPA garbage bag employed process as presented in Figure 49. The LDPE and HDPE pellets were raw materials for PE/starch garbage bags. TDPA additive was purchased from Environmental Product Inc, (EPI).

3) Using

The avoided energy used or waste generation during used for garbage bags. This study presumes that distance from garbage bags factory to user is completely 20 km

4) Transportation

Detailed of raw materials transportation in the entire life cycle of PE/TDPA garbage bag are as follows:

Information of crude oil and natural gas transportation are shown in Appendix Table C5 and Appendix Table C6. Distance of materials transportation for LDPE and HDPE production is shown in Appendix Table D3. This study presumes that distance from factory to factory is completely 2 km. Information of

LDPE and HDPE pellets transportation were calculated based on average distance from Rayong province to garbage bag factory at Nakornpatom province in Thailand, as shown in Appendix Table D4. Information of TDPA additive transportation were calculated based on average distance from New Zealand and Australia to garbage bag factories at Nakornpatom province in Thailand, as shown in Appendix Table D5.

2.1.3 LCI data of PE garbage bag

The LCI data from the production of PE garbage bag consist of six stage including raw material extraction (crude oil and natural gas), raw materials preparation (ethylene), HDPE LDPE, and LDPE production, PE garbage bag manufacturing, using, and transportation. Detailed information of LCI data in each process are as follows:

1) Raw materials extraction

- Crude oil and natural gas exploration

Detailed information of crude oil exploration and natural gas extraction have already presented in Appendix Table C1 and Appendix Table C2.

2) Materials preparation

Ethylene was raw material for HDPE LDPE and LLDPE which supplemented from SimaPro 7.0 database and national life cycle inventory database project (MTEC, 2009a), respectively.

3) HDPE, LDPE and LLDPE production

Information of HDPE was supplemented from SimaPro 7.0 database while LDPE and LLDPE were supplemented from National life cycle inventory database project (MTEC, 2009a), respectively.

4) PE garbage bag production

Information of PEgarbage bag production was also reviewed national life cycle inventory database project (MTEC, 2009a). Data of this report collected from PE/photo garbage bag 50% of total capacity production of Thailand. PE garbage bag production consists of 5 main steps including mixing, blowing and printing, cutting, and recycling process. PE garbage bag employed process as presented in Figure 49. The inventory data of PE garbage bag, raw materials was from HDPE, LDPE and LLDPE pellet.

5) Using

The avoided energy used or waste generation during used for garbage bags. This study presumes that distance from garbage bags factory to user is completely 20 km.

6) Transportation

Detailed of raw material in the entire life cycle of PE garbage bag are as follow:

Information of crude oil and natural gas transportation are shown in Appendix Table C 5 and Appendix Table C6. Distance of materials transportation for HDPE, LDPE and LLDPE production are shown in Appendix Table D3. This study presumes that distance from factory to factory is completely 2 km. Information of HDPE, LDPE and LLDPE pellets transportation were calculated based on average distance from Rayong province to garbage bag factory at Nakornpatom province in Thailand, as shown in Appendix Table D4.

2.1.4 Distance to waste management of PE/starch, PE/TDPA, and PE garbage bag

Detailed information for transportation to waste management of PE/starch, PE/TDPA, and PE garbage bags are shown in Table 25.

Table 25 Distance of garbage bags transportation to municipal solid waste (MSW).

Original-Destination	Amount (kg)			vehicle	Distance 1 way (km)
	PE/starch	PE/TDPA	PE		
Waste collection (Bangkok)- Incineration	416.83	79.22	60.83	Truck	21.94
Waste collection (Bangkok)-Compost	416.83	79.22	60.83	Truck	97.85
Waste collection (Bangkok)-Landfill	416.83	79.22	60.83	Truck	97.85

2.1.5 Waste management of garbage bags

The following waste treatment scenarios for PE/starch, PE/TDPA, and PE garbage bags were considered. The LCI data of waste management scenarios in this section are summarized as follows:

1) PE/starch, PE/TDPA, and PE, are disposed by 90% landfill and 10% incineration. The LCI data of landfill and incineration of garbage bags are shown in Table 26.

2) PE/starch, PE/TDPA, and PE, are disposed by incineration. The LCI data of incineration of garbage bags are shown in Table 27.

Table 26 LCI data of landfill of 90% and incineration of 10% per functional unit of garbage bags.

Type	PE/starch	PE/TDPA	PE	Unit
Mass/Energy input				
Waste	416.83	93.174	65.486	kg
Electricity	2.084	0.465	0.327	kWh
Land used for landfill	4,636.43	4,886.29	4,963.89	m^2
Land used for incineration	140.26	140.26	140.26	m^2
Mass/Energy output				
Air emissions				
CO_2 emission	115.15	25.78	20.67	kg
CH_4 emission	13.228	1.18	0.53	kg
Solid waste				
Waste from landfill	334.47	81.15	57.94	kg
Waste from incineration	10.42	2.33	1.64	kg

3) PE/starch, PE/TDPA, and PE, are disposed by incineration with heat recovery. The LCI data of incineration with heat recovery of garbage bags are shown in Table 28.

Table 27 LCI data of incineration per functional unit of garbage bags.

Type	PE/starch	PE/TDPA	PE	Unit
Mass/Energy input				
Waste	416.83	93.174	65.486	kg
Electricity	20.842	4.658	3.274	kWh
Land used for incineration	1,402.56	1,402.56	1,402.56	m^2
Mass/Energy output				
Air emissions				
CO_2 emission (kg)	787.34	225.14	192.09	kg
Solid waste				
Waste from incineration	104.21	23.29	16.37	kg

Table 28 LCI data of incineration and heat recovery per functional unit of garbage bags.

Type	PE/starch	PE/TDPA	PE	Unit
Mass/Energy input				
Waste	416.83	93.174	65.486	kg
Electricity	20.842	4.658	3.274	kWh
Land used for incineration	1,402.56	1,402.56	1,402.56	m^2
Mass/Energy output				
Crude oil	-33.89	-7.70	-5.88	kg
Natural gas	-283.87	-83.02	-63.42	kg
Coal	-105.92	-24.06	-18.38	kg
Air emissions				
CO_2 emission	787.34	225.14	192.09	kg
Solid waste				
Waste from incineration	104.21	23.29	16.37	kg

4) PE/starch, PE/TDPA, and PE are disposed by landfill. The LCI data of landfill of garbage bags are shown in Table 29.

The results of weight changes of PE/starch, PE/TDPA, and PE samples after incubation in the landfill are presented in Figure 43. An example of picture (images) of the samples studied PE/starch, PE/TDPA, and PE samples under landfill condition as a function of time are present in Figure 44, Figure 45 and Figure 46, respectively. As a previous section, the results of temperature and pH during landfill test are shown in Table 15, which are favorable for microbial activity.

It is found that the degradation of PE/starch is only 8.18% after 20 months. It has been observed that PE with starch (30%) is also not susceptible to microbial degradation in the natural landfill environment, although it has been known that starch is readily degradation by a wide variety of microorganism. The swelling at the starch granule can be detected within 3 moths, which become more deformation in the hydrophilic surface of PE/starch, as shown in Figure 44. However, swollen granule of the polymer matrix is not occurred in high fraction since almost all surface of PE/starch is uniform matrix by the high portion of PE.

The small weight loss of 3.23% is observed for PE with pro-oxidant (TDPA) as shown in Figure 45, which agrees with Mohee *et al.* (2008). Mohee *et al.* (2008) had studied the biodegradability of PE/TDPA and found that the PE/TDPA did not biodegrade under anaerobic and aerobic condition. Moreover, it can be noted that the condition in the landfill at 32.5-62.0 ^{o}C resulted in an insignificant degradation mechanism (thermal oxidation) in TDPA.

The weight loss of PE in the natural landfill shows 1.69%, indicating that there is no biodegradation. Figure 46 shows the uniform continuous surface of PE after biodegradation testing of 20 months.

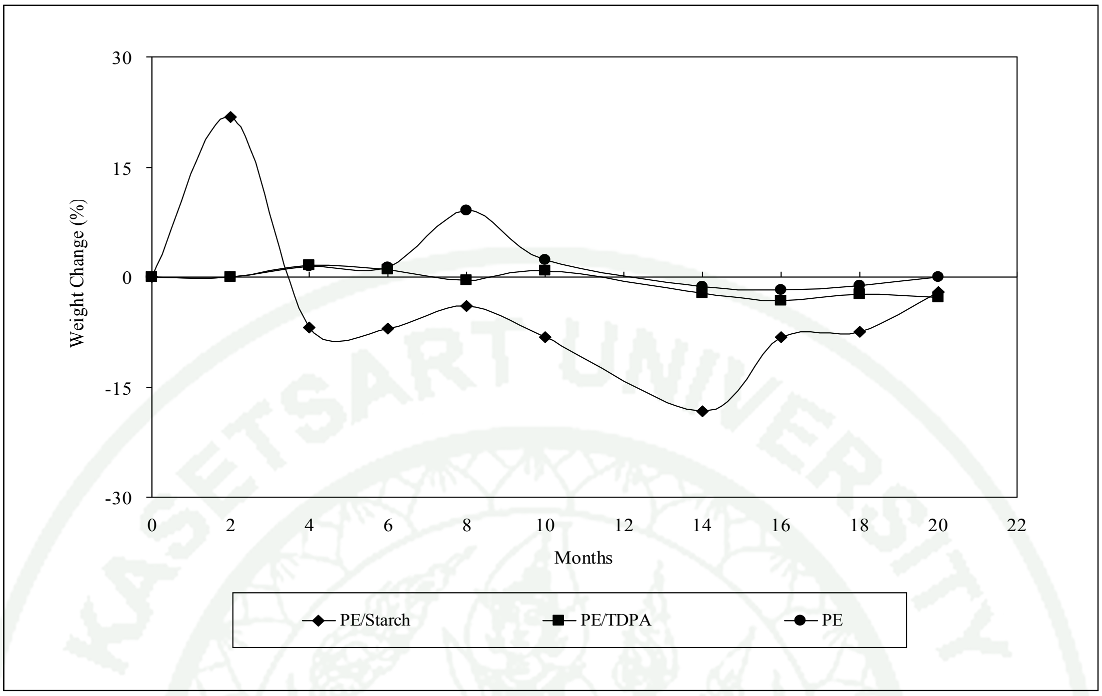
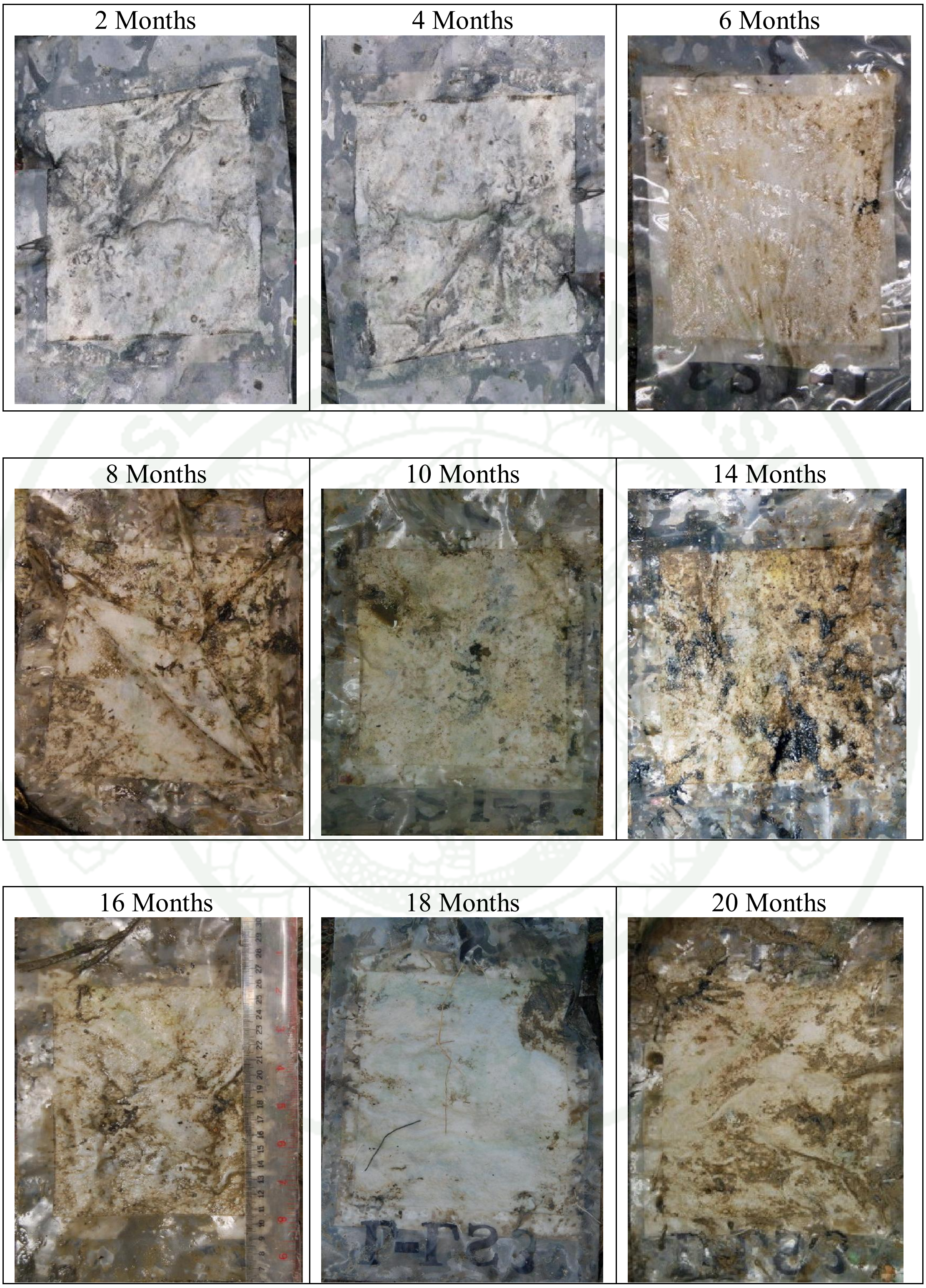


Figure 43 Weight changes PE/starch, PE/TDPA, and PE after incubation in the landfill as a function of time.

The LCI data of garbage bags from the natural landfill carried out in Thailand of 20 months, as shown in Table 29.

Table 29 LCI data of landfill per functional unit of garbage bags.

Type	PE/starch	PE/TDPA	PE	Unit
Mass/Energy input				
Waste	416.83	93.174	65.486	kg
Land used for landfill	5,151.58	5,429.21	5,515.43	m^2
Mass/Energy output				
CO_2 emission (kg)	40.42	3.63	1.62	kg
CH_4 emission (kg)	14.64	1.32	0.59	kg
Solid waste				
Waste from landfill	382.75	90.16	64.38	kg



2 Months
4 Months
6 Months
8 Months
10 Months
14 Months
16 Months
18 Months
20 Months

Figure 44 Degradation of PE/starch garbage bag under landfill conditions as a function of time.

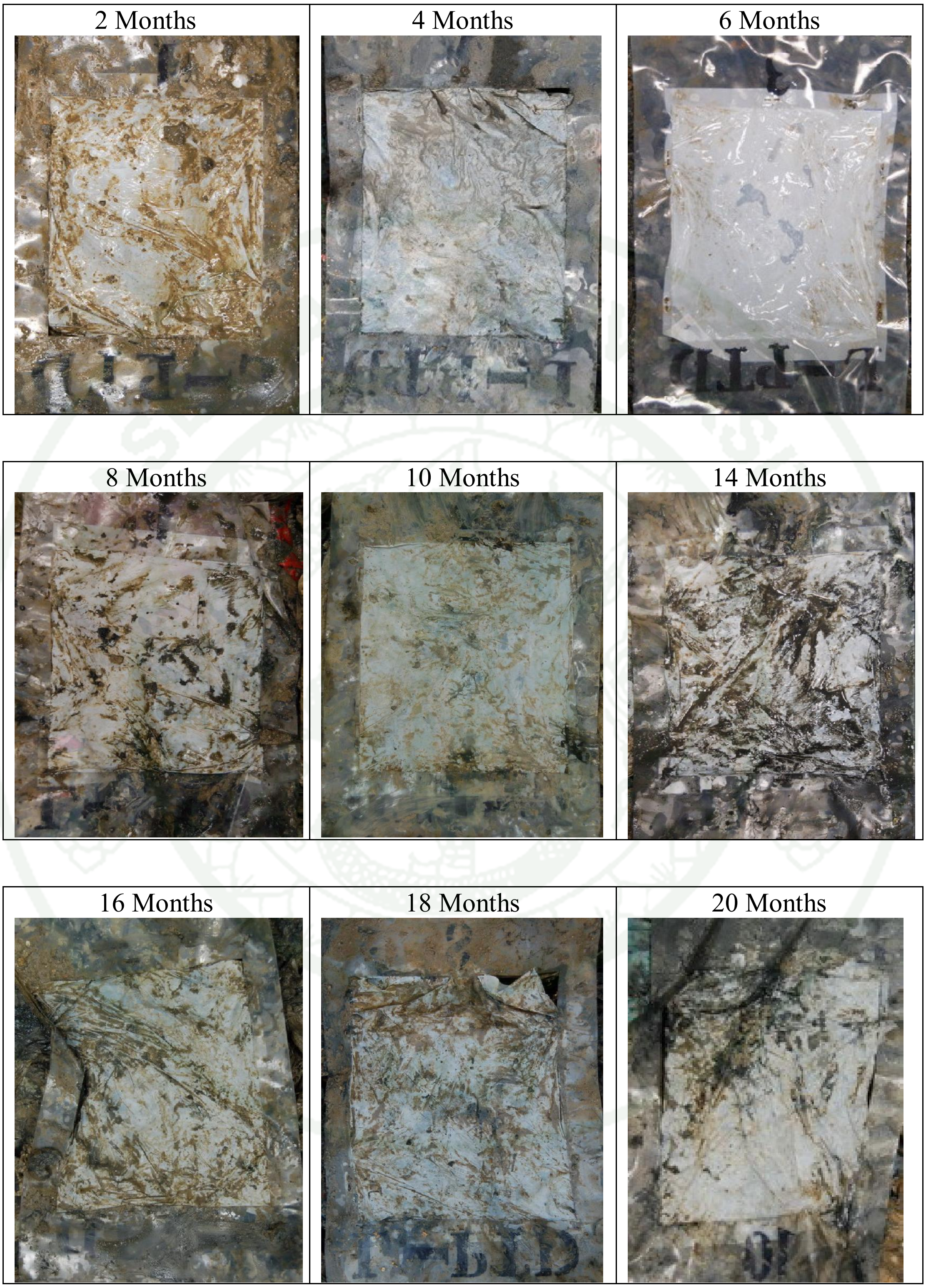
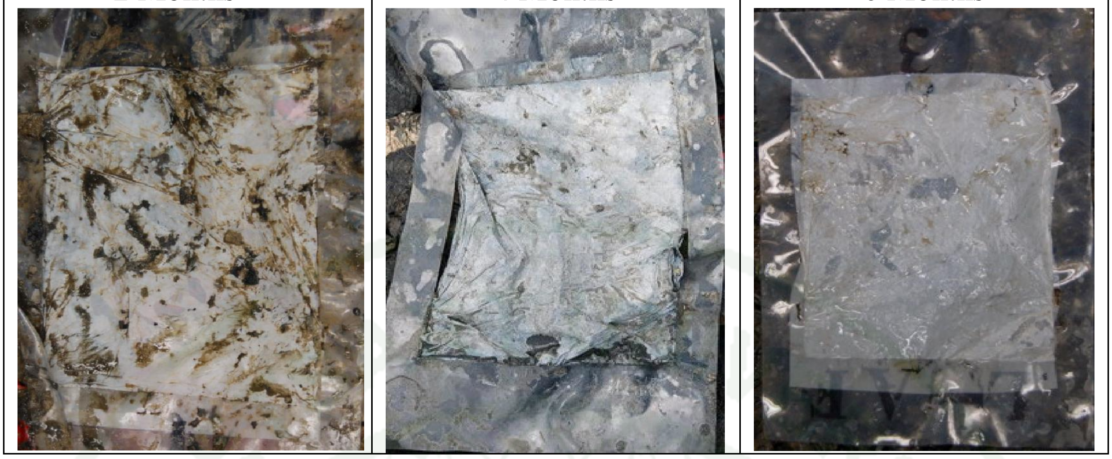

2 Months
4 Months
6 Months
8 Months
10 Months
14 Months
16 Months
18 Months
20 Months

Figure 45 Degradation of PE/TDPA garbage bag under landfill conditions as a function of time.


2 Months | 4 Months | 6 Months


8 Months | 10 Months | 14 Months


16 Months | 18 Months | 20 Months

Figure 46 Degradation of PE garbage bag under landfill conditions as a function of time.

5) PE/starch, PE/TDPA, and PE are disposed by landfill with energy recovery from methane collection

The LCI data of Landfill with energy recovery from methane collection was from both experiment and Bohmann (2004). The LCI results of the calculation are summarizes in Table 30.

Table 30 LCI data of landfill with energy recovery per functional unit of garbage bags.

Type	PE/starch	PE/TDPA	PE	Unit
Mass/Energy input				
Waste	416.83	93.174	65.486	kg
Land used for landfill	5,151.58	5,429.21	5,515.43	m^2
Mass/Energy output				
Electricity	-101.26	-9.09	-4.06	kWh
CO_2 emission	40.42	3.63	1.62	kg
CH_4 emission	3.67	0.33	0.15	kg
Solid waste				
Waste from landfill	382.75	90.16	64.38	kg

6) PE/starch, PE/TDPA, and PE, are disposed by composting.

The biodegradability potential of PE/starch, PE/TDPA, and PE are performed in an aerobic degradation condition as per ISO 14855-99. As composting is an aerobic biological treatment, it presumes that CH_4 emissions are not generated. The biodegradability potential of PE/starch and PE are 11.5% and 0.56%, respectively. Whereas, the biodegradability potential of PE/TDPA is 0.02%, which was supplement data from Mohee *et al*. (2008). Similarly, this is interesting to assess the heavy metals in the compost. Detailed information of composting obtained from garbage bags are shown in Table 31.

Table 31 LCI data of composting per functional unit of garbage bags.

Type	PE/starch	PE/TDPA	PE	Unit
Mass/Energy input				
Waste	416.83	93.174	65.486	kg
Organic agricultural waste	5,001.9	1,118.1	785.8	kWh
Air	393.93	0.173	3.705	kg
Land used	5,192.68	5,577.69	5,308.62	m^2
Mass/Energy output				
Air emissions				
CO_2 emission (kg)	113.75	0.05	1.07	kg
Emissions to soil				
Compost	5,387.78	1,210.72	847.80	kg
- Waste plastics	385.81	92.63	61.96	kg
- Fertilizer N	–	–	–	kg
- Fertilizer P	–	–	–	kg
- Fertilizer K	–	–	–	kg
- Carbon sequestration	–	–	–	kg
- As	_	–	–	kg
- Cd	_	–	–	kg
- Cr	5.93-03	1.53E-03	1.07-03	kg
- Cu	–	1.07E-03	–	kg
- Cd	–	7.63E-06	–	kg
- Hg	–	9.16E-04	–	kg
- Pb	1.08E-03	–	6.41E-04	kg
- Zn	_	–	_	kg

7) PE/starch, PE/TDPA, and PE are disposed by 50% landfill and 50% incineration. The LCI data of 50% landfill and 50% incineration of garbage bags are shown in Table 32.

Table 32 LCI data of landfill of 50% and incineration of 50% of garbage bags.

Type	PE/starch	PE/TDPA	PE	Unit
Mass/Energy input				
Waste	416.83	93.174	65.486	kg
Electricity	10.421	2.329	1.637	kWh
Land used for landfill	2,575.79	2,714.60	2757.716310	m^2
Land used for incineration	701.28	701.28	701.278125	m^2
Mass/Energy output				
Air emissions				
CO_2 emission	414.08	114.385	96.857	kg
CH_4 emission	7.349	0.660	0.295	kg
Solid waste				
Waste from landfill	191.377	45.084	32.189	kg
Waste from incineration	52.104	11.646	8.185	kg

2.2 Comparison of energy consumption and environmental impacts and of PE/starch, PE/TDPA, and PE garbage bags.

The results of energy consumption of three types of garbage bags are shown Figure 47. It is found that energy consumption for PE/starch, PE/TDPA, and PE are $2.414x10^4$ MJ/FU, $4.424x10^3$, and $3.490x10^3$ MJ/FU. Among the total energy consumption for PE/starch, PE/TDPA, and PE approximately 57.5%, 67.8%, and 48.8% respectively come from raw materials extraction. The second highest of energy consumption are from garbage bag production of 24.5%, 12.5%, and 33.6% for PE/starch, PE/TDPA, and PE, respectively. Considering raw material extraction, the highest portion of energy consumption comes from crude oil extraction, which account for 84.4%, 73.3%, and 76.2% for PE/starch, PE/TDPA, and PE, respectively. While, the main contribution of energy consumption in garbage bag production comes from chemical used and electricity used.

The comparison of energy consumption of PE/starch, PE/TDPA, and PE garbage bag are shown in Figure 48. It is found that the highest total energy consumption of PE/starch is higher than PE/TDPA and PE garbage bag of 5.4 times, and 6.9 times, respectively. Considering the highest portion of energy consumption of the three types of garbage bags, come from raw materials extraction, followed by material preparation and garbage bag production, respectively. The high consumption of crude oil and natural gas caused by the high consumption of virgin materials and high weight of package that is required to 500,000 liters of garbage bags.

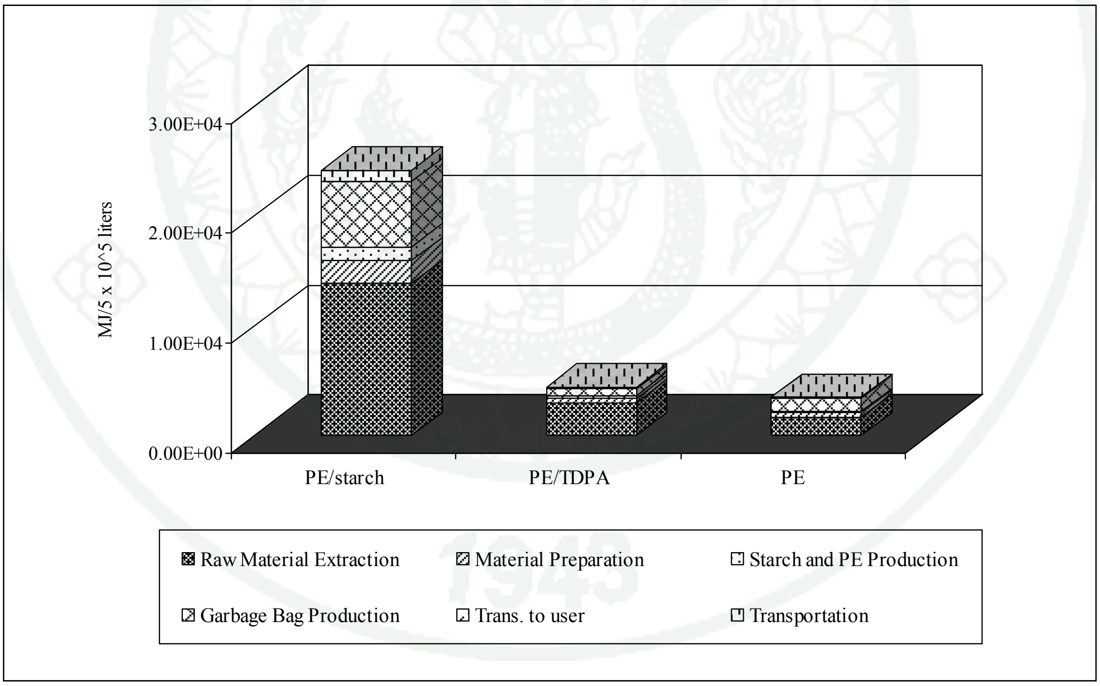


Figure 47 Comparison of the contribution of energy consumption in each phase of PE/starch, PE/TDPA, and PE garbage bags (cradle-to-gate).

2.3 Environmental impacts of PE/starch garbage bags

The assessment of environmental impact (characterization value) in the life cycle assessment (LCA) of PE/starch is shown in Figure 48. It is found that the entire life cycle of PE/starch, in almost all impact categories, crude oil and natural gas extraction and garbage bag production contributed to the highest environmental impact. Similarly, the percentage of environmental impact potentials (characterization value), it can be clearly observed that crude oil and natural gas extraction and garbage bag production give the highest environmental impact potentials in most impact categories. Besides, cassava starch production stage reveals the high contribution for eutrophication impact. The main contribution to photochemical oxidation impact causes mainly from HDPE production.

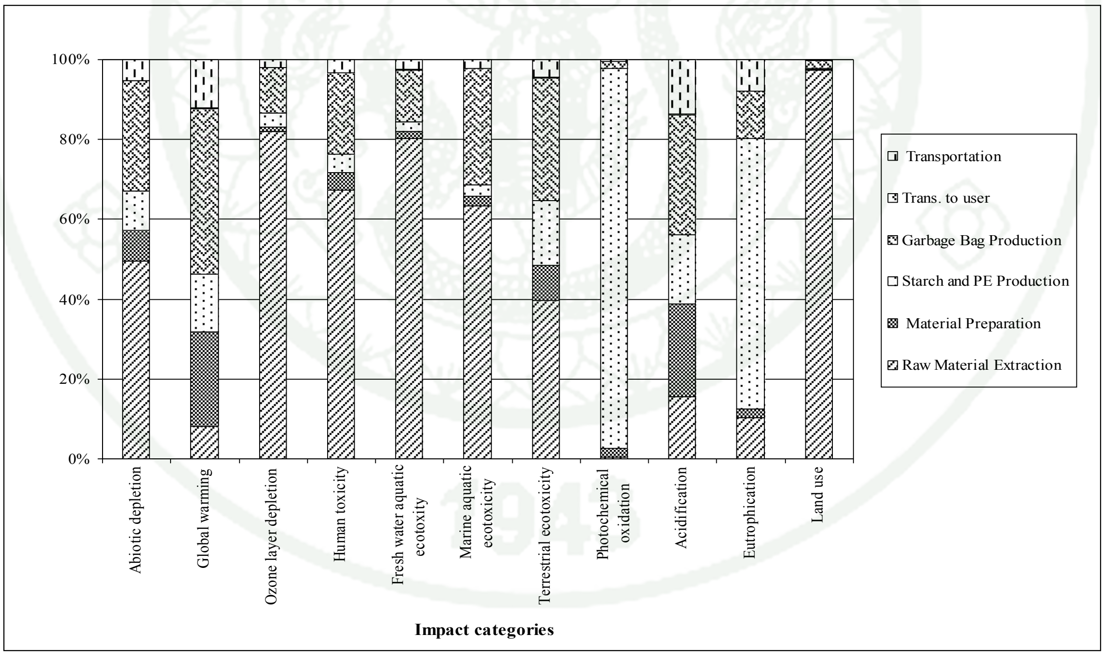


Figure 48 Contribution of environmental impact for PE/starch garbage bags (cradle-to-gate).

2.4 Environmental impacts of PE/TDPA garbage bag

The assessment of environmental impact (characterization value) in the life cycle assessment (LCA) of PE/TDPA garbage bags are shown in Figure 49. It is found that the entire life cycle of PE/TDPA garbage bags, in almost all impact categories also are mostly from crude oil and natural gas extraction and garbage bag production. Similarly, the percentage of environmental impact potentials (characterization value), it can be clearly observed that crude oil and natural gas extraction and garbage bag production give the highest environmental impact potentials in most impact categories excluding global warming, terrestrial ecotoxicity, photochemical oxidation, acidification, eutrophication and land used. Besides, HDPE production stage reveals the high contribution for terrestrial ecotoxicity, photochemical oxidation impact, and land used. Whereas, the main contribution to acidification and global warming impact causes mainly from material preparation, garbage bag production. Considering eutrophication impact, the highest portion of impact comes from transportation and garbage bag production.

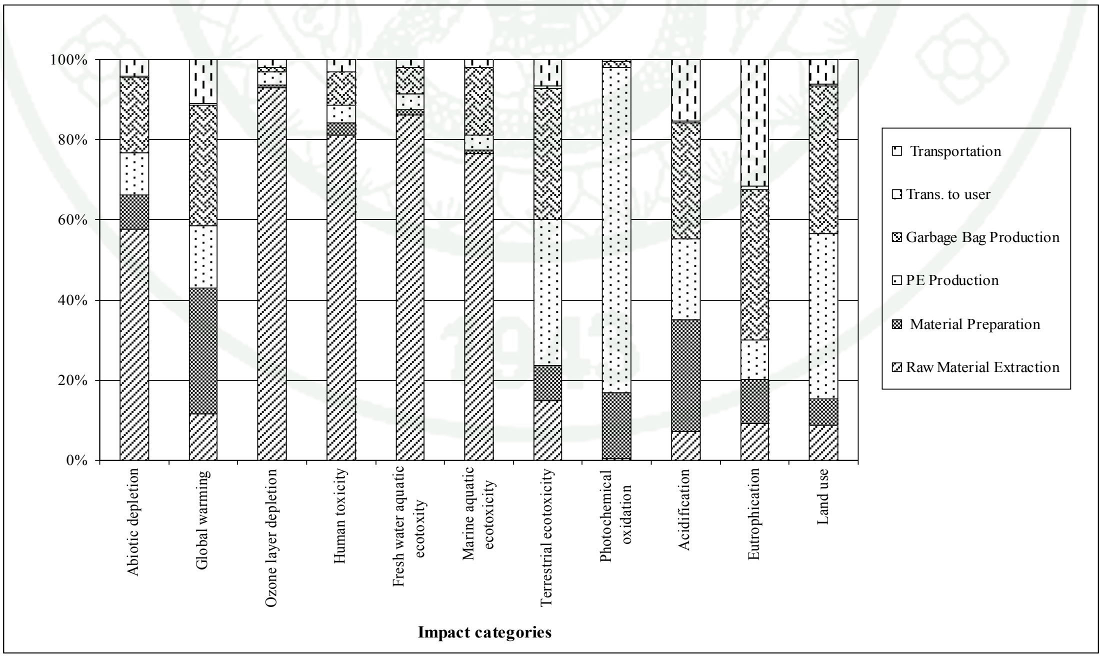


Figure 49 Contribution of environmental impact for PE/TDPA garbage bags (cradle-to-gate).

2.5 Environmental impacts of PE garbage bags

The assessment of environmental impact (characterization value) in the life cycle assessment (LCA) of PE garbage bags is shown in Figure 50. It is found that the entire life cycle of PE garbage bags, in almost all impact categories, crude oil and natural gas extraction and garbage bag production contributed to the highest environmental impact. Similarly, the percentage of environmental impact potentials (characterization value), it can be clearly observed that crude oil and natural gas extraction and garbage bag production give the highest environmental impact potentials in most impact categories excluding photochemical oxidation. As above results, the main contribution to abiotic depletion, global warming, terrestrial ecotoxicity, acidification, eutrophication and land used are caused mainly from garbage bag production. Besides, HDPE production stage reveals the high contribution for photochemical oxidation impact.

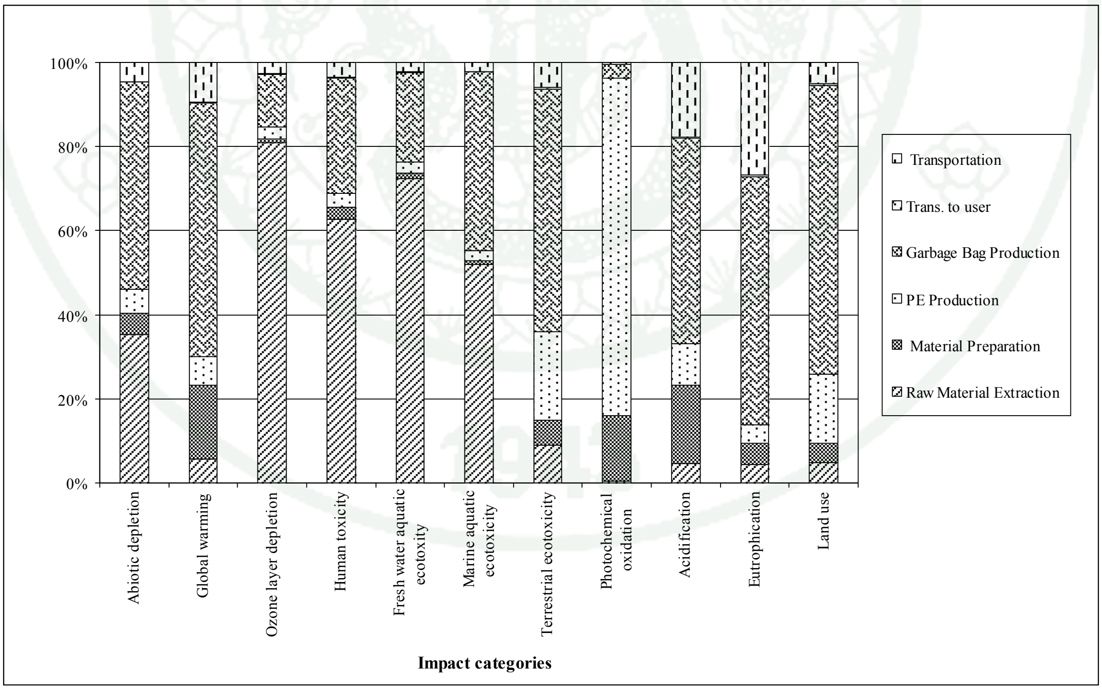


Figure 50 Contribution of environmental impact for PE garbage bags (cradle-to-gate).

2.6 Comparison of environmental impact of PE/starch, PE/TDPA, and PE garbage bags

The comparison of environmental impact from cradle to gate, the percentage of environmental impact potentials (characterization value) is shown in Figure 51. It can be clearly observed that PE/starch garbage bags have 75-99% higher environmental impact than PE/TDPA, and PE garbage bags in all categories. This is due to the higher weight of the PE/starch garbage bags.

Figure 52 shows environmental impact potentials of all impact categories, which are grouped into the single score or the total environmental impact. It is found that the total environmental impact of PE/starch is higher that PE/TDPA, and PE garbage bags of 6.3 times, and 7.1 times, respectively. It is clearly observed that total environmental impact score of PE/starch and PE/TDPA garbage bags are mostly from raw materials extraction and garbage bag production, approximately 56.4-71.4% and 11.7-28.2%, respectively. This is due to it consume virgin materials for HDPE and LDPE pellets. Whereas, PE garbage bags generate the lowest environmental impact because they consume recycling HDPE and LDPE pellets of 29.9% and 19.4% respectively. The causes of impact for PE garbage bags obtain from garbage bag production and raw materials extraction of 44.4% and 43.9%, respectively.

From Figure 53, it is clearly found that PE/starch production give the highest environmental impact potentials in most impact categories. Considering all types of garbage bags, the main environmental load comes from marine aquatic ecotoxicity, abiotic depletion and global warming, which accounts for 90.7-93.5%.

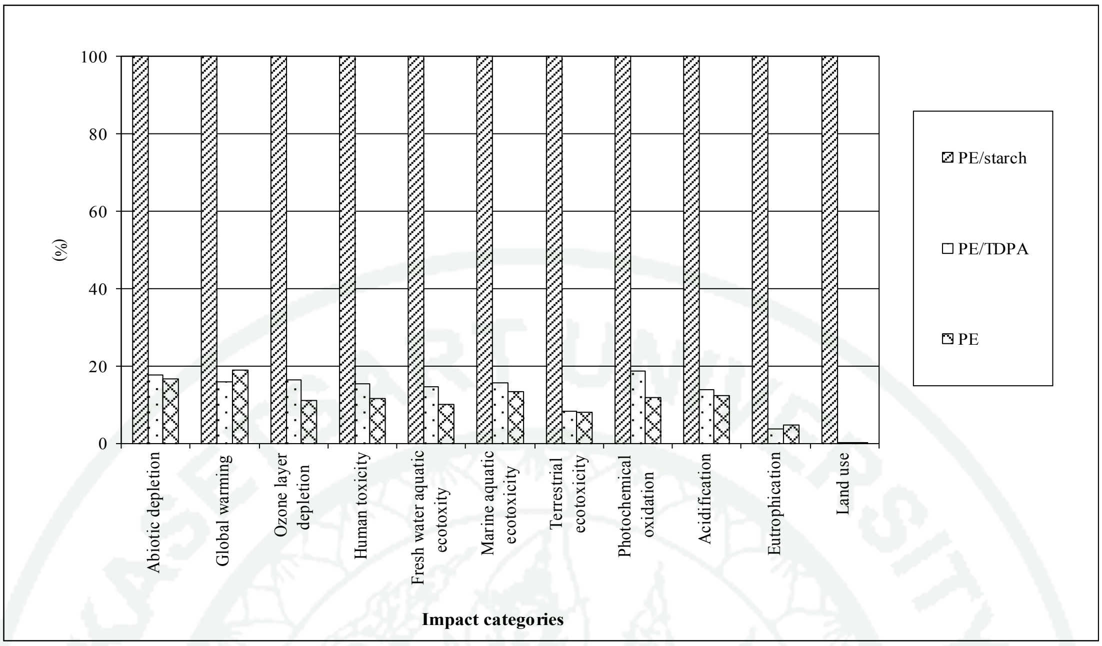


Figure 51 Comparison of the contribution of characterization value of each impact categories of PE/starch, PE/TDPA, and PE garbage bag (cradle-to-gate).

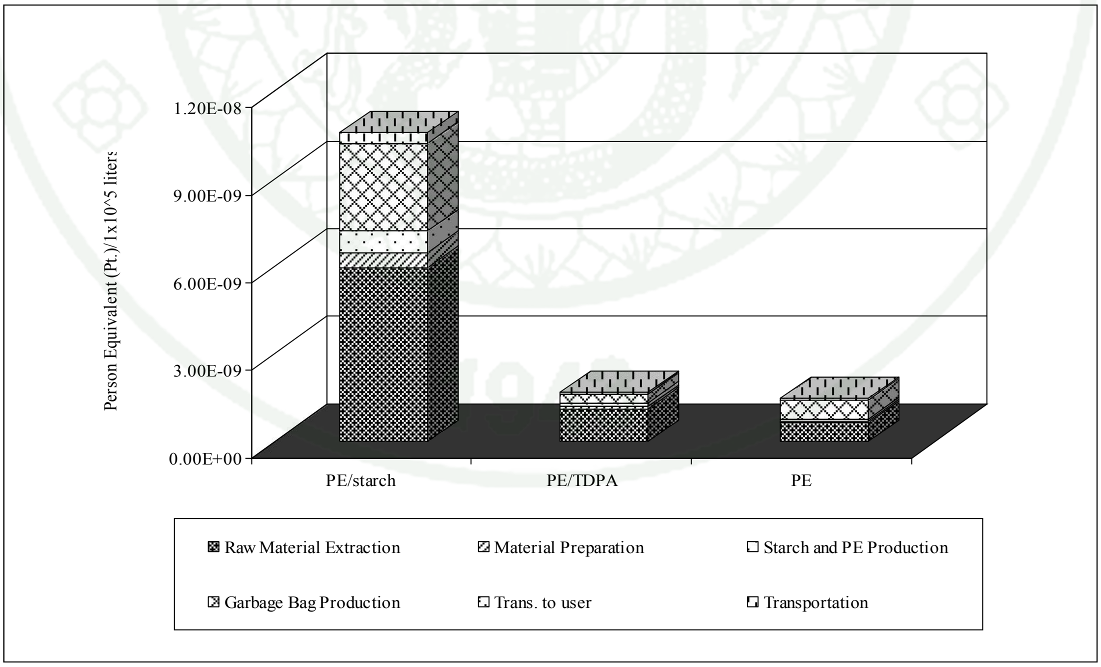


Figure 52 Comparison of total environmental impact scores of each phase of PE/starch, PE/TDPA, and PE garbage bag (cradle-to-gate).

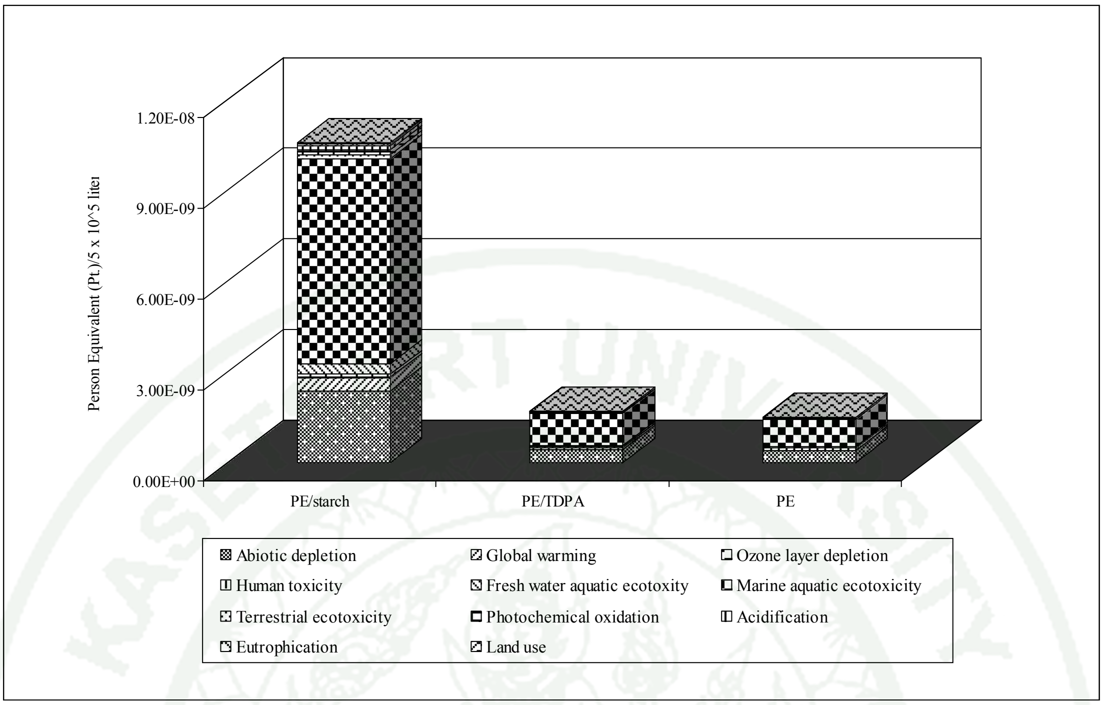


Figure 53 Comparison of total environmental impact scores of PE/starch, PE/TDPA, and PE garbage bags (cradle-to-gate).

2.7 Comparison of energy consumption through whole life cycle of PE/starch, PE/TDPA, and PE of garbage bags.

In a cradle to grave of LCA study, the results from the whole life cycle with end of life management are investigated. The results of life cycle energy consumption for three types of garbage bags are shown in Figure 54. It is found that all garbage bags together with incineration with energy recovery show the favorable option. As mentioned above, the energy produced from incineration leads to preserve energy from the production. In addition, garbage bags with option-5 (landfill with energy recovery from methane collection) shows the good results because of energy product (electricity) from methane collection.

Incineration contributes the highest energy consumption for all garbage bags because high distance to incineration plant and high energy consumption to running incineration plant.

2.8 Comparison of environmental impacts through whole life cycle of PE/starch, PE/TDPA, and PE of garbage bags.

The impact assessment through the whole life cycle with end of life management is considered. The characterization value in a cradle to grave of LCA study for three types of garbage bags, the results of environmental impacts through whole life cycle of PE/starch, PE/TDPA, and PE of garbage bags are shown in Table 33, Table 34, and Table 35, respectively. It can be clearly observed that PE/starch garbage bags have the highest environmental impact of all studied materials. This is due to the higher weight of the PE/starch garbage bags. The assessment results show that raw materials extraction (crude oil and natural) generate the highest environmental impact potentials, as shown in Figure 55.

The worst scenarios of environmental impact for All garbage bags is option 6, where plastics waste is disposed by incineration. The second largest impacts are disposed by incineration, followed by landfill of 90% and incineration of 10%. The main causes come from high amount of combustion emission from incineration.

The comparison of the final weighted score for through the whole life cycle of garbage bags is shown in Figure 55 and Figure 56. It can be observed that the high impact for all degradable materials, PE/starch and PE/TDPA are higher than PE. As above results, this is due to the heavier weight of garbage bags and high used of virgin PE pellets. All garbage bags, the major causes of impact come from high amount of abiotic depletion, global warming, and marine aquatic ecotoxicity, respectively. In addition, plastics are disposed by composting, which reveals the highest contribution for terrestrial ecotoxicity.

The comparison of environmental impact is shown in Figure 56. It is found that all garbage bags with incineration with energy recovery show the best option. The energy produced from incineration leads to reduce environmental impact of garbage bags by 6.7%-12.4%.

In addition, all garbage bags are disposed by landfill with energy recovery from methane collection shows the appropriate results. As mentioned above, energy from methane collection reduces the environmental impact only 0.2%-0.9%.

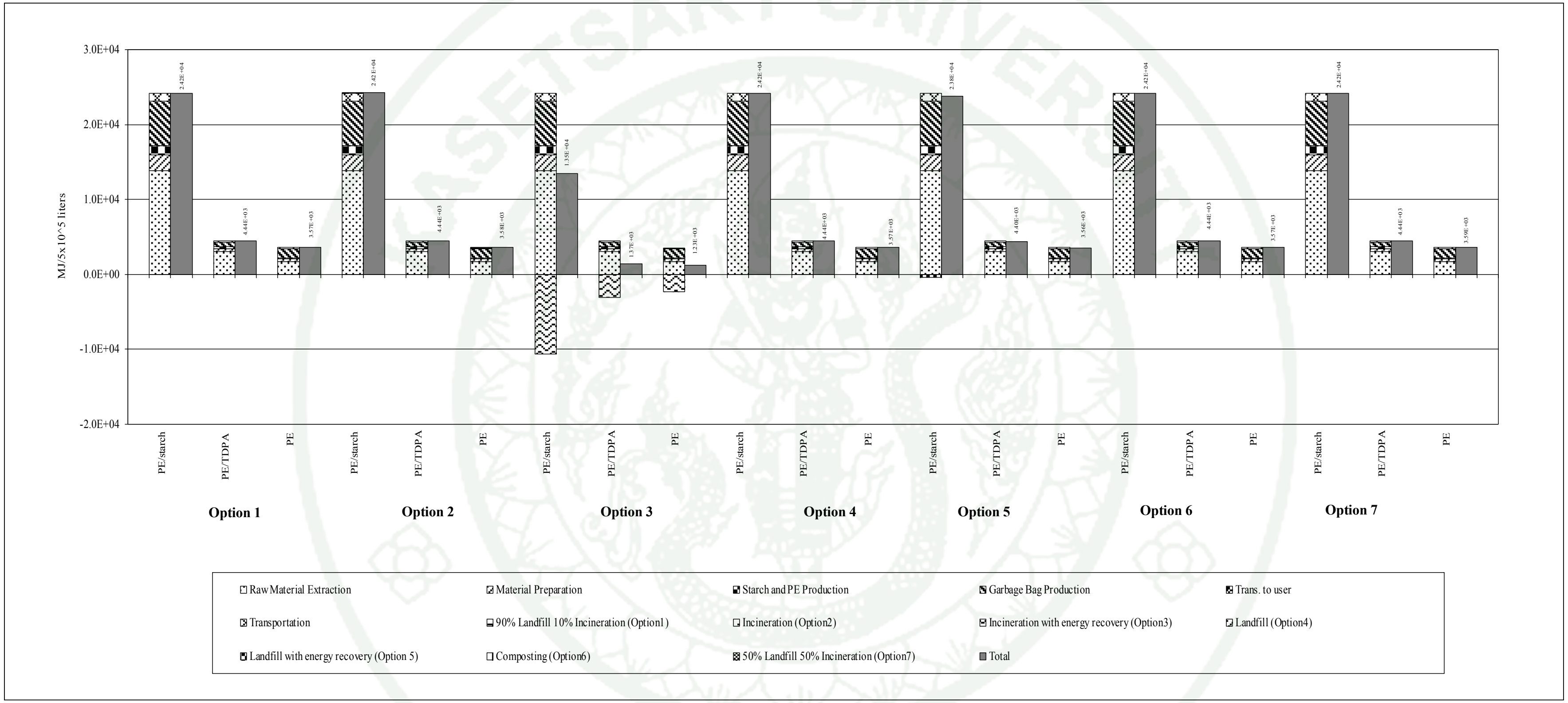


Figure 54 Comparison of energy consumption through life cycle of PE/starch, PE/TDPA, and PE garbage bags (cradle-to-grave).

Table 33 Environmental impact (characterization value) through whole life cycle per functional unit of PE/sstarch (cradle-to-grave).

MSW options / Impact categories	Option-1: 90% landfill, 10% incineration	Option-2: Incineration	Option-3: Incineration-energy recovery	Option-4: Landfill	Option-5 Landfill-energy recovery	Option-6: Composting	Option-7: 50% landfill, 50% incineration	Unit
Abiotic depletion	1.41E+01	1.42E+01	1.21E+01	1.41E+01	1.33E+01	1.40E+01	1.41E+01	kg Sb eq
Global warming	1.46E+03	1.84E+03	8.70E+02	1.42E+03	1.11E+03	1.15E+03	1.63E+03	kg CO2 eq
Ozone layer depletion	8.27E-04	8.26E-04	8.26E-04	8.28E-04	8.28E-04	8.26E-04	8.27E-04	kg CFC-11eq
Human toxicity	5.41E+02	5.40E+02	4.73E+02	5.41E+02	5.41E+02	5.42E+02	5.41E+02	kg 1,4-DB eq
Fresh water aquatic	1.44E+02	1.44E+02	1.25E+02	1.44E+02	1.44E+02	1.44E+02	1.44E+02	kg 1,4-DB eq
Marine aquatic	5.32E+05	5.31E+05	4.63E+05	5.32E+05	5.32E+05	5.31E+05	5.32E+05	kg 1,4-DB eq
Terrestrial ecotoxicity	2.61E+00	2.60E+00	1.76E+00	2.61E+00	2.61E+00	2.63E+00	2.60E+00	kg 1,4-DB eq
Photochemical oxid.	4.41E+00	4.33E+00	4.26E+00	4.42E+00	4.35E+00	4.33E+00	4.38E+00	kg C2H4
Acidification	5.90E+00	5.89E+00	3.67E+00	5.90E+00	5.76E+00	5.86E+00	5.90E+00	kg SO2 eq
Eutrophication	2.32E+00	2.32E+00	1.98E+00	2.32E+00	2.30E+00	2.31E+00	2.32E+00	kg PO4 eq
Land use	5.16E+03	1.79E+03	1.79E+03	5.54E+03	5.54E+03	5.58E+03	3.66E+03	m2yr

Table 34 Environmental impact (characterization value) through whole life cycle per functional unit of PE/TDPA (cradle-to-grave).

options / Impact categories	Option-1: 90% landfill, 10% incineration	Option-2: Incineration	Option-3: Incineration-energy recovery	Option-4: Landfill	Option-5 Landfill-energy recovery	Option-6: Composting	Option-7: 50% landfill, 50% incineration	Unit
Abiotic depletion	2.56E+00	2.58E+00	2.10E+00	2.55E+00	2.48E+00	2.55E+00	2.57E+00	kg Sb eq
Global warming	2.11E+02	3.84E+02	1.64E+02	1.92E+02	1.86E+02	1.58E+02	2.88E+02	kg CO2 eq
Ozone layer depletion	1.37E-04	1.37E-04	1.37E-04	1.37E-04	1.37E-04	1.37E-04	1.37E-04	kg CFC-11eq
Human toxicity	8.53E+01	8.50E+01	6.98E+01	8.53E+01	8.53E+01	8.61E+01	8.52E+01	kg 1,4-DB eq
Fresh water aquatic	2.12E+01	2.11E+01	1.68E+01	2.12E+01	2.12E+01	2.19E+01	2.12E+01	kg 1,4-DB eq
Marine aquatic	8.46E+04	8.44E+04	6.89E+04	8.46E+04	8.46E+04	8.48E+04	8.45E+04	kg 1,4-DB eq
Terrestrial ecotoxicity	2.29E-01	2.26E-01	3.59E-02	2.29E-01	2.29E-01	7.00E-01	2.27E-01	kg 1,4-DB eq
Photochemical oxid.	7.16E-01	7.09E-01	6.92E-01	7.17E-01	7.17E-01	7.09E-01	7.13E-01	kg C2H4
Acidification	8.60E-01	8.58E-01	3.54E-01	8.60E-01	8.48E-01	8.60E-01	8.59E-01	kg SO2 eq
Eutrophication	9.07E-02	9.00E-02	1.37E-02	9.08E-02	8.87E-02	9.08E-02	9.04E-02	kg PO4 eq
Land use	5.03E+03	1.40E+03	1.40E+03	5.43E+03	5.43E+03	5.58E+03	3.42E+03	m2yr

Table 35 Environmental impact (characterization value) through whole life cycle per functional unit of PE (cradle-to-grave).

options Impact categories	Option-1: 90% landfill, 10% incineration	Option-2: Incineration	Option-3: Incineration-energy recovery	Option-4: Landfill	Option-5 Landfill-energy recovery	Option-6: Composting	Option-7: 50% landfill, 50% incineration	Unit
Abiotic depletion	2.37E+00	2.39E+00	2.02E+00	2.37E+00	2.34E+00	2.37E+00	2.38E+00	kg Sb eq
Global warming	2.13E+02	3.73E+02	2.05E+02	1.95E+02	1.83E+02	1.81E+02	2.84E+02	kg CO2 eq
Ozone layer depletion	9.29E-05	9.27E-05	9.25E-05	9.29E-05	9.29E-05	9.29E-05	9.28E-05	kg CFC-11eq
Human toxicity	6.46E+01	6.44E+01	5.28E+01	6.46E+01	6.46E+01	6.51E+01	6.45E+01	kg 1,4-DB eq
Fresh water aquatic	1.49E+01	1.48E+01	1.16E+01	1.49E+01	1.49E+01	1.49E+01	1.49E+01	kg 1,4-DB eq
Marine aquatic	7.28E+04	7.27E+04	6.08E+04	7.28E+04	7.28E+04	7.29E+04	7.28E+04	kg 1,4-DB eq
Terrestrial ecotoxicity	2.21E-01	2.19E-01	7.35E-02	2.21E-01	2.21E-01	2.42E-01	2.20E-01	kg 1,4-DB eq
Photochemical oxid.	4.55E-01	4.52E-01	4.39E-01	4.56E-01	4.53E-01	4.52E-01	4.54E-01	kg C2H4
Acidification	7.67E-01	7.66E-01	3.80E-01	7.67E-01	7.62E-01	7.67E-01	7.66E-01	kg SO2 eq
Eutrophication	1.12E-01	1.11E-01	5.31E-02	1.12E-01	1.11E-01	1.12E-01	1.12E-01	kg PO4 eq
Land use	5.11E+03	1.40E+03	1.40E+03	5.52E+03	5.52E+03	5.31E+03	3.46E+03	m2yr

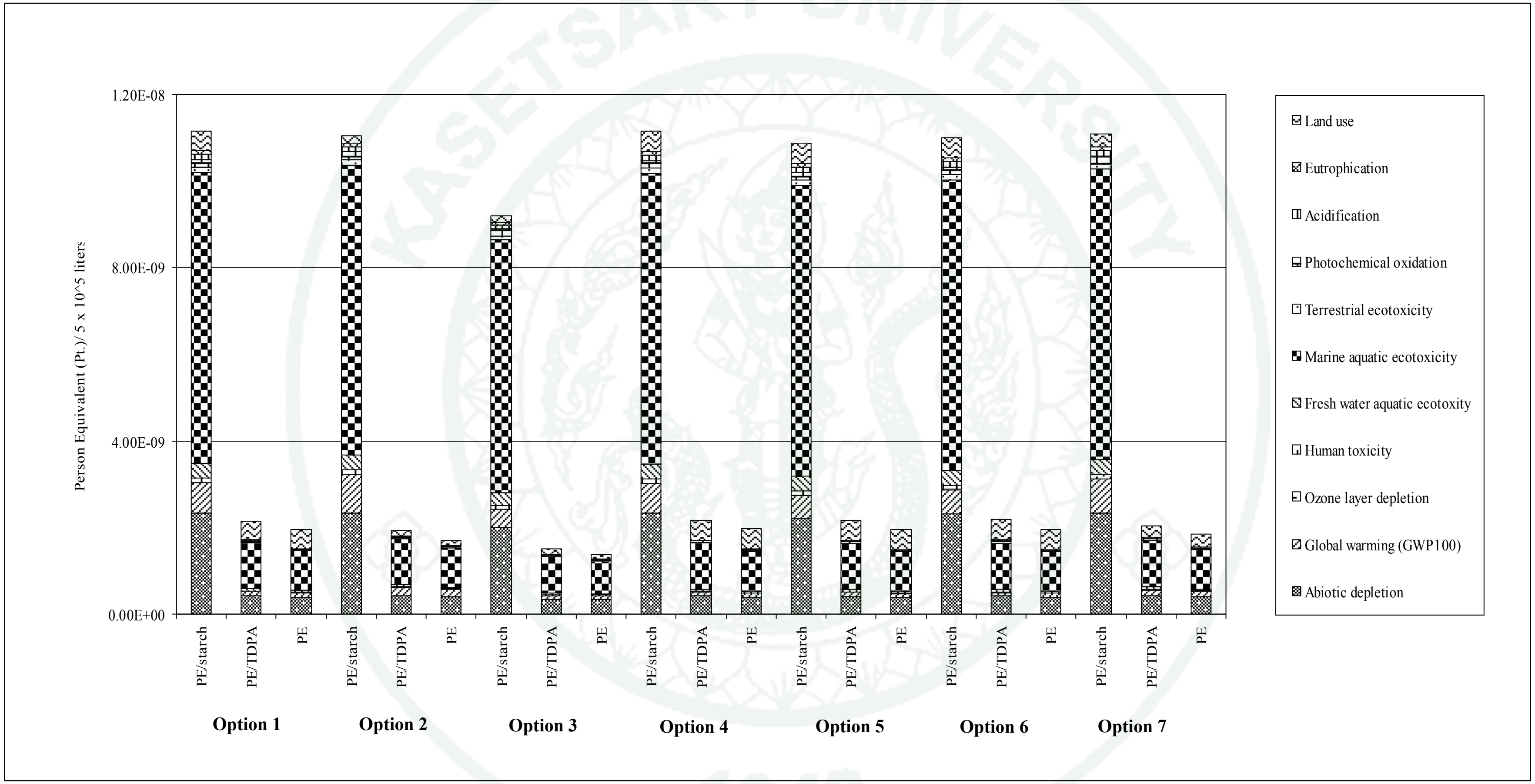


Figure 55 Comparison of the total environmental impacts through whole life cycle per functional unit of PE/starch, PE/TDPA, and PE garbage bags (cradle-to-grave).

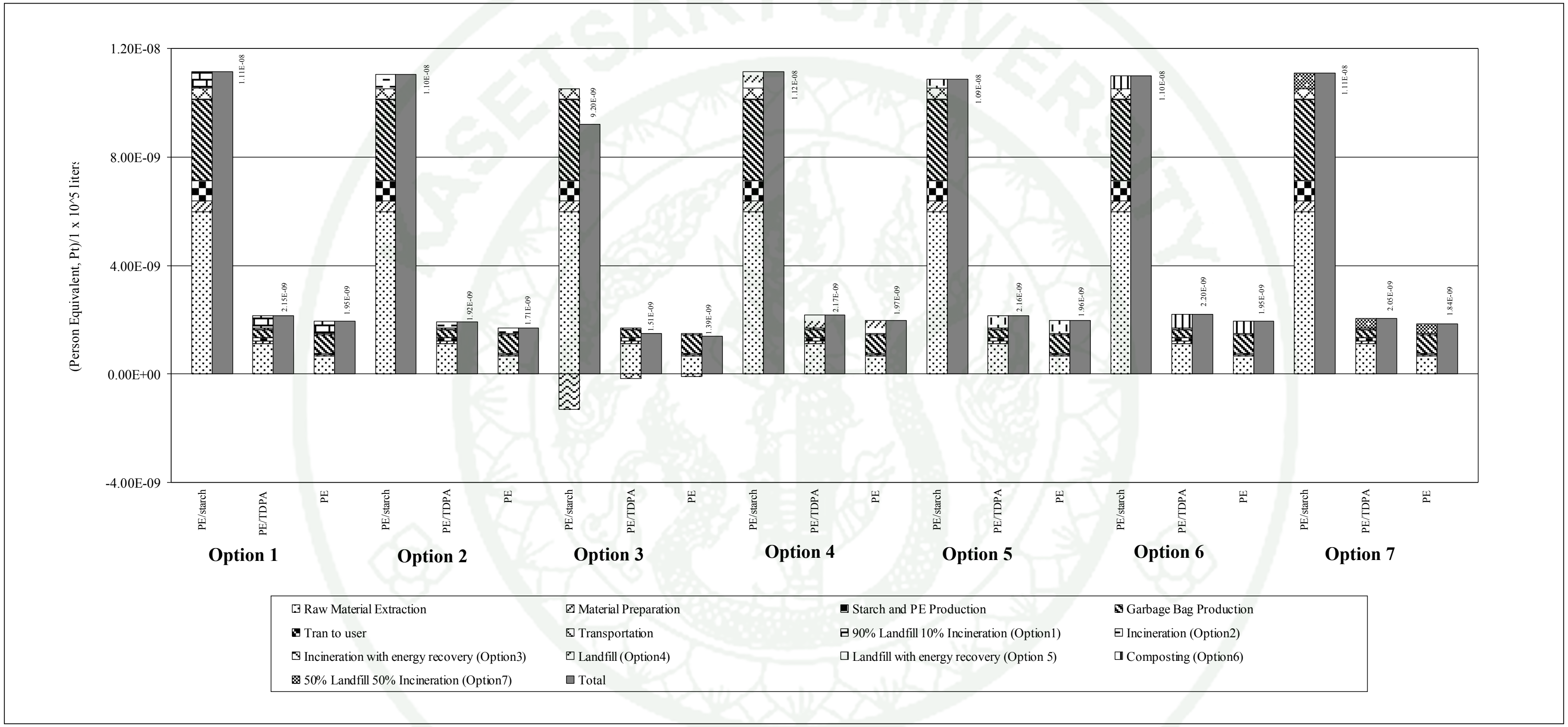


Figure 56 Comparison of the total environmental impacts score of each process through whole life cycle per functional unit of PE/starch, PE/TDPA, and PE garbage bags (cradle-to-grave).

2.9 Improvement

In this section, hypothesis for the improvements of the process based on the results obtains from LCA study. Detailed information of improvement scenarios for each plastic are described as follows.

2.9.1 PE/starch improved

From the previous results, the energy consumption and environmental impact of the production of the PE/starch garbage bags are mostly from crude oil and natural gas extraction and heavier weight of PE/starch garbage bags. In the next LCA study, the following improvement scenarios for PE/starch garbage bags are described as follows:

1) Using recycling PE pellets in garbage bag manufacturing (PE/starch-improved 1).

2) Using biogas process in starch production for PE/starch (PE/starch-improved 2).

3) Using the ratio of PE/starch at 50/50 (PE/starch-improved 3).

4) Using the ratio of PE/starch at 70/30 (PE/starch-improved 4).

5) Reducing the amount of materials usage in forming process of 10% (PE/starch-improved 5).

6) Reducing the amount of materials usage in forming process of 50% (PE/starch-improved 6).

7) The improvement of hypothetical PE/starch-improved includes using recycling PE pellets in garbage bag manufacturing, using biogas

process in starch production, using the ratio PE/starch of 50/50, and reducing the amount of materials usage in forming process of 10% (PE/starch-improved 7).

8) The improvement of hypothetical PE/starch -improved includes using recycling PE pellets in garbage bag manufacturing, using biogas process in starch production, using the ratio PE/starch of 70/30, and reducing the amount of materials usage in forming process of 10% (PE/starch-improved 8).

2.9.2 Energy consumption of PE/starch garbage bags with process improvement (PE/starch-improved)

The comparison of energy consumption of PE/starch garbage bags and PE/starch-improved are presented in Figure 57. Major cause of lower energy consumption in each case PE/starch-improved are summarized as follows:

Firstly, using recycling PE pellets in garbage bag manufacturing leads to saving energy consumption of 9.182×10^3 MJ which is 38.1 % lower than that of from the PE/starch-baseline. Second, since biogas process are used in starch production, reduce fossil energy consumption of 7.15610^2 MJ resulted in reduction of energy from the base case only 3.02%. Third, the improvement, the ratio of PE pellets and starch, are used at the portion of 50% to 50% and 30% to 70%, respectively. As mentioned above, these could lead to reduce fossil energy consumption of 8.723×10^3 MJ and 12.070×10^3 MJ which are 36.2 % and 50.1% respectively lower than that of from the PE/starch-baseline. Fourth, the following improvement reduces material consumption by 10% or 50% lead to saving energy consumption of 2.394×10^3 MJ and 12.025×10^3 MJ which are 9.9% and 49.8% respectively lower than that of from the PE/starch-baseline.

Finally, PE/starch-improved 7, the improvement of hypothetical PE/starch garbage bags, includes using recycling PE pellets in garbage bag manufacturing, using biogas process are used in starch production, preparation the ratio of PE pellets and starch at 50% to 50%, and reducing the amount of materials usage in garbage bag manufacturing of 10%. Therefore, PE/starch-improved 7 has 48.6% lower energy consumption than the PE/starch-baseline. While, PE/starch-improved 8 has 22.85% lower energy consumption than the PE/starch-improved 7 and 71.50% lower energy consumption than the PE/starch-baseline because high ratio of cassava starch consumption for PE/starch garbage bags of 70%.

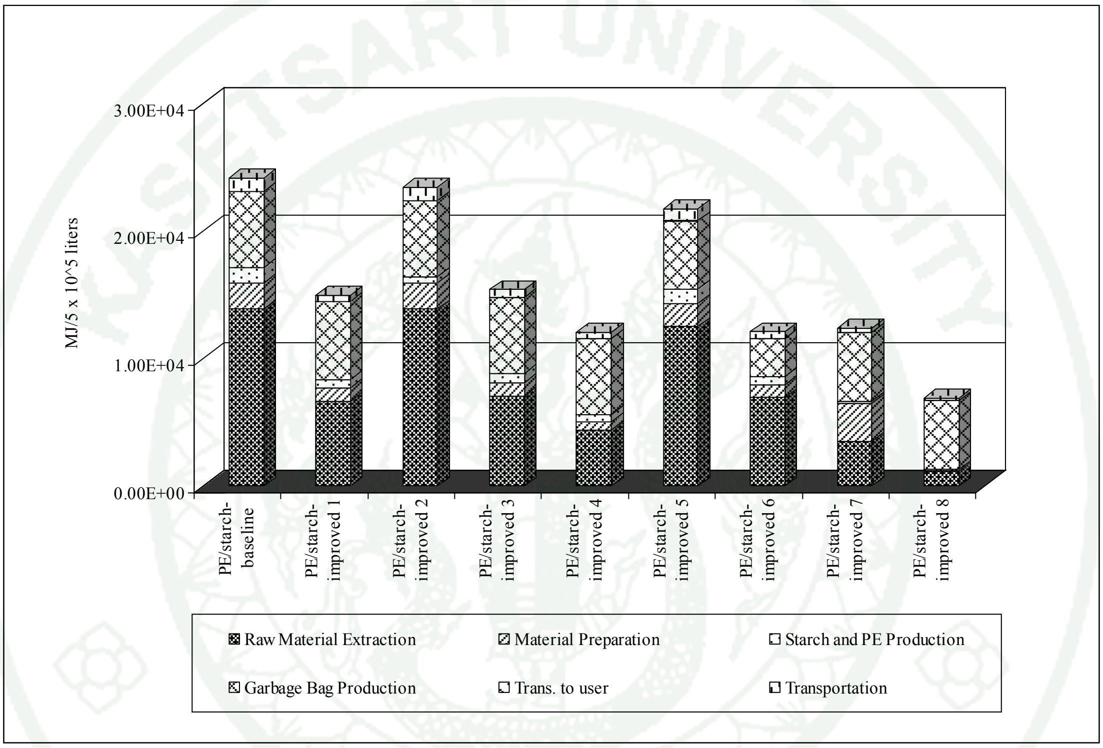


Figure 57 Comparison of the contribution of energy consumption in each phase of PE/starch-baseline and PE/starch-improved (cradle-to-gate).

2.9.3 Environmental impact of PE/starch garbage bags with process improvement (PE/starch -improved)

Figure 58 shows the comparison of environmental impact potentials of all impact categories, which are grouped into the single score or the total environmental impact. It is found that the total environmental impact of PE/starch-baseline is higher that PE/starch-improved of 1.0-3.5 times. Major causes of impact of PE/starch-improved also come from abiotic depletion, marine aquatic ecotoxicity, and global warming, which accounts for 88.6%–91.7%. The environmental impact potentials of each phase in the whole life cycle of PE/starch-improved, the main load is from raw materials extraction (crude oil and natural gas) and garbage bag production, which account for 85.3%-94.6% as shown in Figure 59.

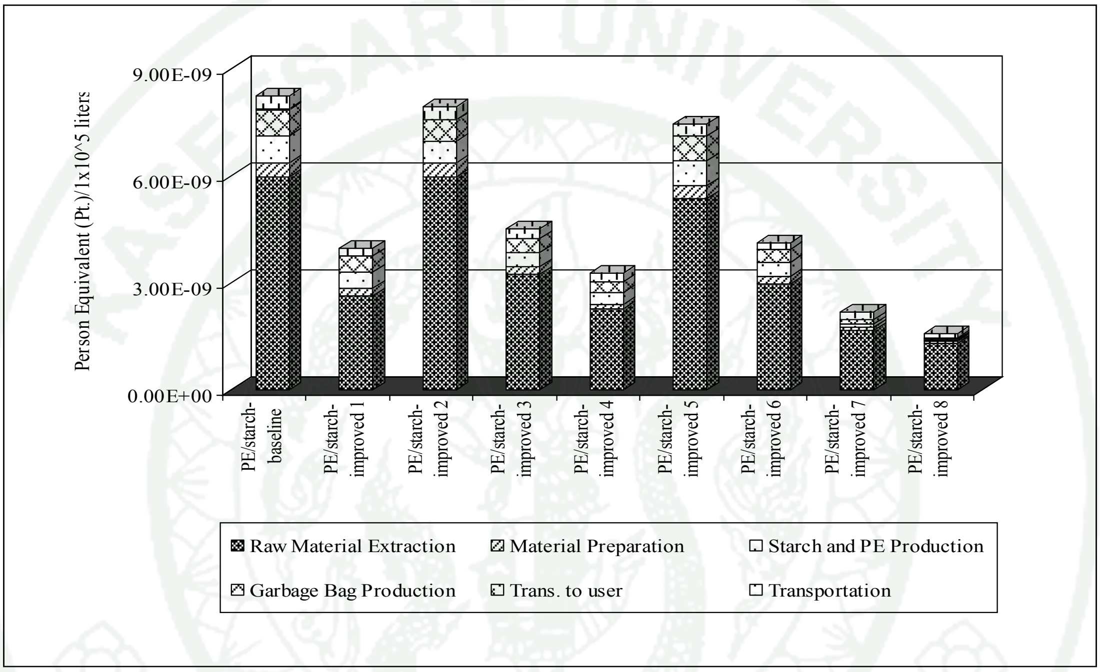


Figure 58 Comparison of the total environmental impact score in each phase of PE/starch-baseline and PE/starch-improved (cradle-to-gate).

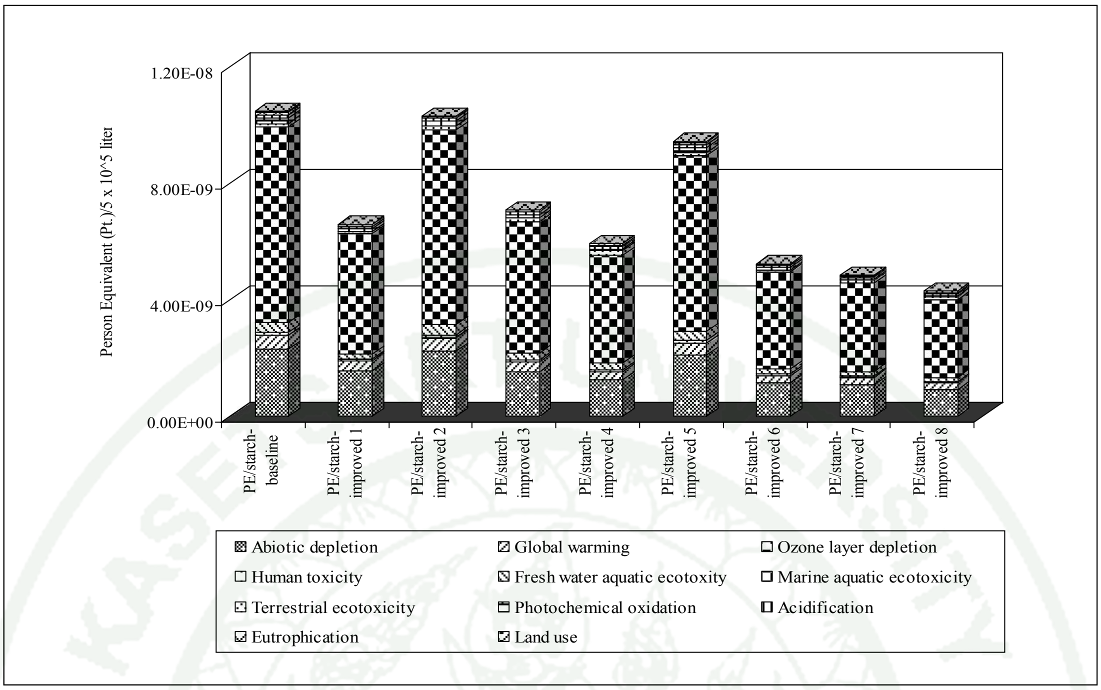


Figure 59 Comparison of the total environmental impact score of PE/starch-baseline and PE/starch-improved (cradle-to-gate).

2.10 The comparison to the other studies (cradle-to-gate)

The comparison of the energy consumption and GHG emissions per kg of HDPE, LDPE, and LLDPE pellets are within the range of the data from obtained other sources, as shown in Table 36 and Table 37, respectively.

Table 36 Comparison of energy consumption of HDPE, LDPE, and LLDPE pellets with the other studies (Unit: MJ/kg).

Types	This study	SimaPro 7 (2008)[1]	SimaPro 7 (2008)[2]	PlasticsEU (2008)	Bastiolio (2005)
HDPE	71.20	74.00	79.90	_	73.80
LDPE	95.08	92.70	_	91.81	91.70
LLDPE	90.30	74.00	73.80	_	73.80

Note: 1 is Simapro 7 (2008) data from B 250
2 is Simapro 7 (2008) data from ETH U

Table 37 Comparison of the GHG emission of HDPE, LDPE, and LLDPE pellets with the other studies (Unit: kg CO_2 eq./kg).

Types	This study	SimaPro 7 (2008)[1]	SimaPro 7 (2008)[2]	PlasticsEU (2008)	Bastiolio (2005)
HDPE	1.64	2.11	_	1.89	_
LDPE	2.14	3.07	_	1.93	_
LLDPE	2.01	2.15	1.55	_	_

Note: 1 is Simapro 7 (2008) data from B 250
2 is Simapro 7 (2008) data from ETH U

The comparison of GHG emissions per kg of PE/starch, PE/starch-improved 1, PE/TDPA, and PE garbage bag are within the range of the data from obtained other sources are shown in Table 38. The GHG emissions per kg of PE/starch are quite higher than the literature due to usage virgin PE pellets. While, PE/starch improved-1 consume recycling of 50% total PE pellets, which contribute to close the literature data.

Table 38 Comparison of the GHG emission of PE/starch, PE/starch-improved 1, PE/TDPA, and PE garbage bag with the other studies (Unit: MJ/kg).

Types	This study		Jame and Grant	SimaPro 7	
	IPCC- 2001	Eco- 95	(2005)	(2008)[1]	(2008)[2]
PE/starch	2.11	1.95	1.52	–	–
PE/starch –improved 1	1.67	1.59	1.52	–	–
PE/TDPA	1.77	1.62	2.02	–	–
PE	2.49	2.35	2.65	1.63	1.74

Note: 1 is SimaPro 7 (2008) data from LLDPE film recycled FAL
2 is SimaPro 7 (2008) data from LDPE film recycled FAL

2.11 Carbon footprint

The comparison of life cycle GHG emissions (carbon footprint) is shown in Figure 60. For the first part of this study, the production of PE/starch, PE/TDPA, and PE garbage bags are considered.

The highest GHG emission comes from garbage bag production of 41%-50% due to GHG emission from electricity used. Besides, it can be clearly observed that garbage bag manufacturing of PE garbage bag has the highest portion of GHG emission. As mentioned above, an increase in electricity for recycling PE pellets increases the amount of GHG emissions. The GHG emission of PE/starch shows the highest impact in all materials study (5.3-6.3 times). It can be seen that the higher weigh of package results in high energy and material consumption.

In the second part, the whole life cycle with the different waste management scenarios of PE/starch, PE/TDPA, and PE garbage bags are considered.

The result shows that incineration and heat recovery also shows a good result, followed by landfill with energy recovery from methane collection. The experiment results, composting and landfill are not suitable MSW options because it is not decomposed. The assessment results show that the GHG emissions from waste management stage generates the highest GHG emissions, where the plastics are disposed by option 2 (incineration), followed by option 7 (landfill of 50% and incineration of 50%), and option 1 (landfill of 90% and incineration of 10%). This is due to the high CO_2 emission from incineration and landfill. Moreover, CH_4 emissions contribute the high GHG emission because the greenhouse gas of CH_4 is 21 times that of CO_2. As above results, it can be observed that an increase in incineration content increases the amount of GHG emissions for plastics due to combustion emission from incineration.

2.12 Sensitivity analysis

The influences of heavy metals of disposed by composting were considered. Figure 61 shows the total environmental impact of all garbage bags with disposal by composting with based on heavy metals from plastics (option 6) and heavy metals from plastics together with inoculumns (option 6*). It is clearly observed that since heavy metals emission consist of inoculums and plastics waste, total environmental impact score of garbage bags with composting (option 6*) are increased from the base case.

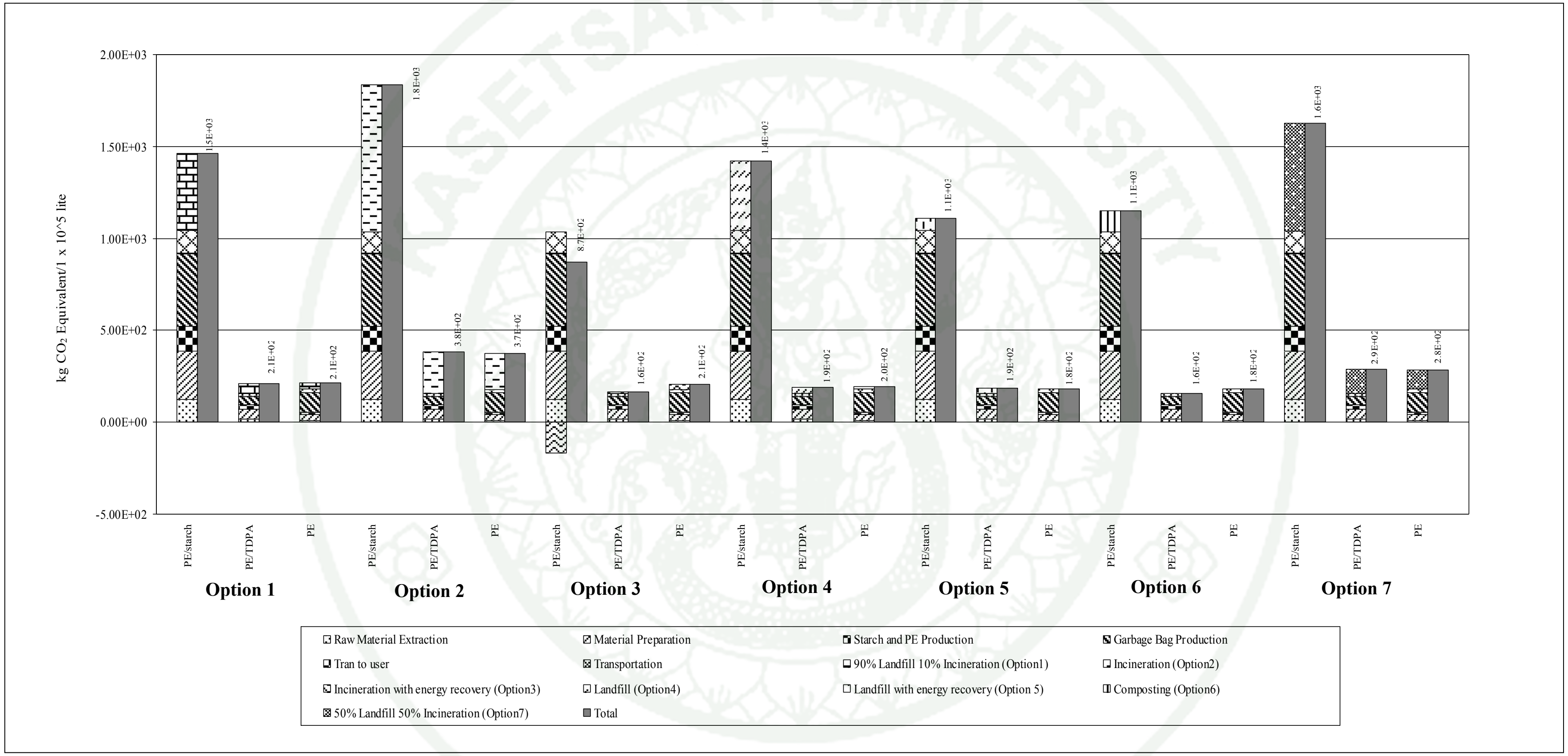


Figure 60 Comparison of GHG emission through life cycle PE/starch, PE/TDPA, and PE garbage bags (cradle-to-grave).

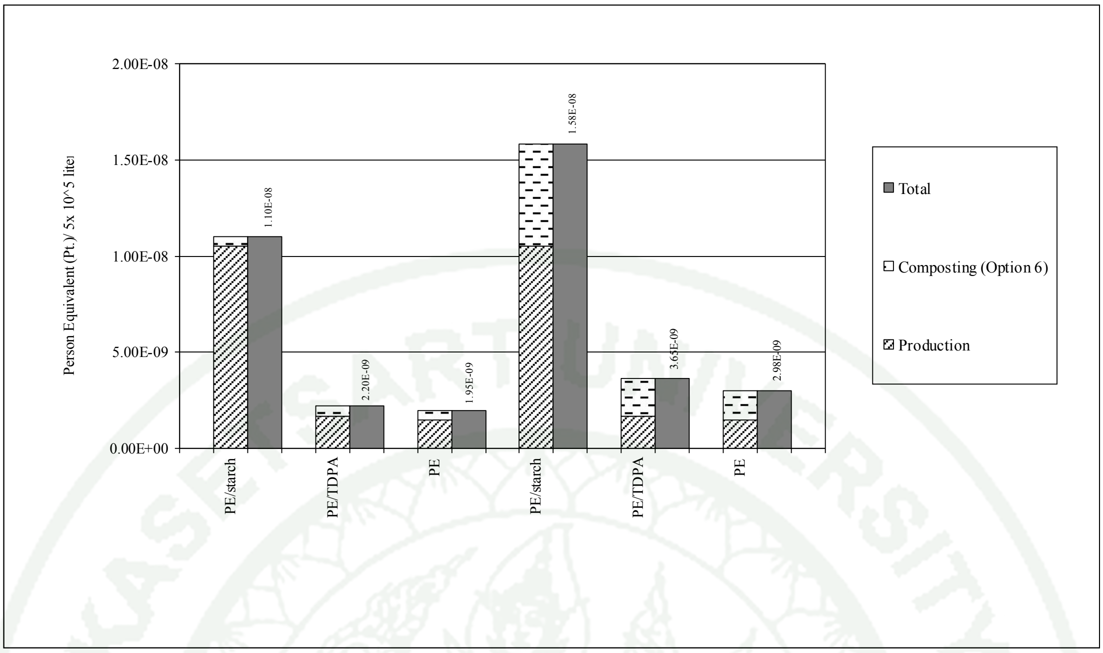


Figure 61 Comparison of sensitivity of the total environmental impact score through whole life of garbage bags with composting with based on heavy metals from plastics and heavy metals from plastics together with inoculumns.

3. Kinetic model

3.1 Rate equation for degradation of plastic materials

The corresponding kinetic model has been developed from Komilis (2006). The change of three types of dry solid carbon into intermediate (water-soluble carbon), are illustrated in Equationท (32)-(44). The change of water-soluble is illustrated in Equation (35). The mineralization of water-soluble carbon into carbon dioxide is illustrated in Equation (36). The degradation of each organic material in the composting similar consists of two stages: primary solid hydrolysis followed by aerobic microbial activity. The readily, moderately and slowly hydrolysable solid carbon fractions represent external degradation in the first step of primary solid hydrolysis. Internal cell degradation expresses the mineralization from intermediate solid carbon to carbon dioxide, biomass, and water. The mechanism is illustrated in Figure 62.

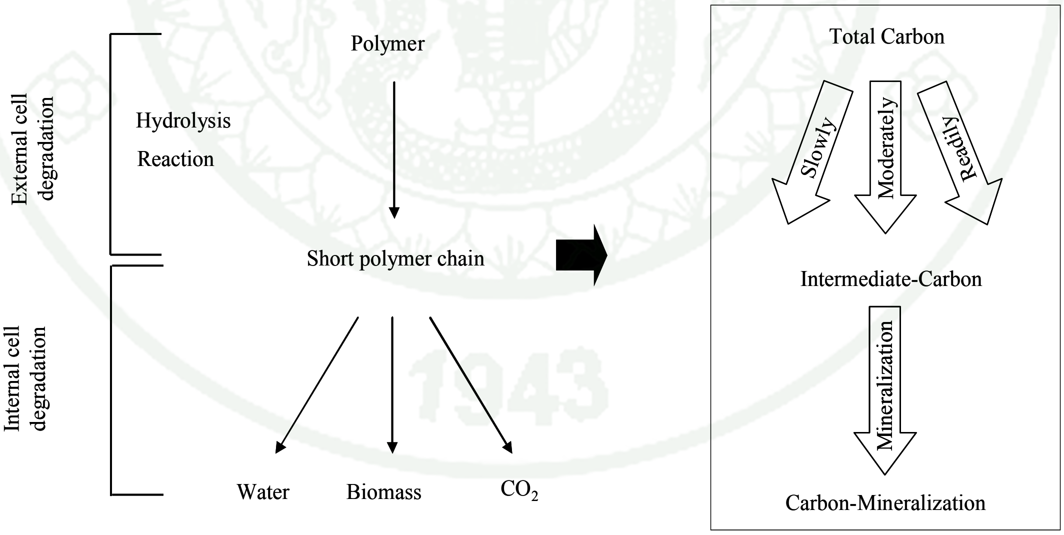


Figure 62 Flowchart of enzyme degradation (left) and carbon degradation (right) during aerobic composting.

$$\frac{dC_r}{dt} = -k_{hr} \cdot C_r\,, \tag{32}$$

$$\frac{dC_m}{dt} = -k_{hm} \cdot C_m\,, \tag{33}$$

$$\frac{dC_s}{dt} = -k_{hs} \cdot C_s\,, \tag{34}$$

$$\frac{dC_{aq}}{dt} = \left(k_{hr} \cdot C_r + k_{hm} \cdot C_m + k_{hs} \cdot C_s\right) - \left(k_{aq} \cdot C_{aq}\right), \tag{35}$$

$$\frac{dC_T}{dt} = k_{aq} \cdot C_{aq}\,, \tag{36}$$

where, t = t-c; c is lag time before C-CO_2 (C_T) product evolves (day); t is time (day).

3.2 Analytical solutions for degradable of organic carbon

The analytical solutions of Equations (37)-(39) are obtained by applying the numerical method using an integrating factor to solve Equations (32)-(34). For Equation (40), the initial condition is $C_{aq} = C_{aq0}.e^{-kaq.(t-c)}$ at $t = 0$. The analytical equation expresses the change of dry solid carbon into intermediate solid carbon and the change of intermediate solid carbon into carbon dioxide.

$$C_{r\_t} = C_{r0} \cdot e^{-k_{hr} \cdot (t-c)} \quad \text{for } t > c \text{ or } 0 \text{ for } t \le c, \tag{37}$$

$$C_{m\_t} = C_{m0} \cdot e^{-k_{hm} \cdot (t-c)} \quad \text{for } t > c \text{ or } 0 \text{ for } t \le c, \tag{38}$$

$$C_{s\_t} = C_{s0} \cdot e^{-k_{hs} \cdot (t-c)} \quad \text{for } t > c \text{ or } 0 \text{ for } t \le c, \tag{39}$$

$$C_{aq\_t} = C_{aq0} \cdot e^{-k_{aq} \cdot (t-c)} + C_{r0} \cdot k_{hr} \cdot \frac{(e^{-k_{hr} \cdot (t-c)} - e^{-k_{aq} \cdot (t-c)})}{k_{aq} - k_{hr}}$$

$$+ C_{m0} \cdot k_{hm} \cdot \frac{(e^{-k_{hm} \cdot (t-c)} - e^{-k_{aq} \cdot (t-c)})}{k_{aq} - k_{hm}} + C_{s0} \cdot k_{hs} \cdot \frac{(e^{-k_{hs} \cdot (t-c)} - e^{-k_{aq} \cdot (t-c)})}{k_{aq} - k_{hs}} \qquad (40)$$

$$C_{T\_t} = \left(\begin{array}{l} C_{aq0} \cdot (1 - e^{-k_{aq} \cdot (t-c)}) \\ + \left[C_{r0} \cdot \left(1 - \frac{k_{aq}}{k_{aq} - k_{hr}} \cdot e^{-k_{hr} \cdot (t-c)} + \frac{k_{hr}}{k_{aq} - k_{hr}} \cdot e^{-k_{aq} \cdot (t-c)} \right) \right] \\ + \left[C_{r0} \cdot \left(1 - \frac{k_{aq}}{k_{aq} - k_{hr}} \cdot e^{-k_{hr} \cdot (t-c)} + \frac{k_{hr}}{k_{aq} - k_{hr}} \cdot e^{-k_{aq} \cdot (t-c)} \right) \right] \\ + \left[C_{s0} \cdot \left(1 - \frac{k_{aq}}{k_{aq} - k_{hs}} \cdot e^{-k_{hs} \cdot (t-c)} + \frac{k_{hs}}{k_{aq} - k_{hs}} \cdot e^{-k_{aq} \cdot (t-c)} \right) \right] \end{array} \right)$$

for $t > c$ or 0 for $t \leq c$, (41)

where, C_{T_t} is percentage of cumulative C-CO_2 product at time t; C_{r_t}, C_{m_t}, C_{s_t} are percentages of readily, moderately and slowly hydrolysable solid carbon fractions at time t, respectively; C_{aq_t} is percentage of intermediate solid carbon at time t; C_{r0}, C_{m0}, C_{s0} are percentages of initial readily, moderately and slowly hydrolysable solid carbon fraction, respectively; C_{aq0} is percentage of initial intermediate solid carbon at time t; k_{hr}, k_{hm}, k_{hs} are readily, moderately and slowly hydrolysis rate constant (day^{-1}); k_{aq} is mineralization rate constant (day^{-1}).

A model curve fitting was used to calculate rate constant for the cumulative carbon released as CO_2 during degradation of materials. A first order reaction in series with a flat lag phase for degradation is illustrated in Equation (41). Therefore, each material at a specific aerobic biodegradable condition gives the constant values of k_{haq}, k_{hr}, k_{hm}, C_{r0}, C_{m0}, C_{s0}, and C_{aq0}. The non-linear regression analysis in Excel Solver was used to solve this problem. The solutions minimize the objective function by using a quasi-Newton method (Chapra *et al.,* 2002).

The mathematical constraints were also developed from Komilis (2006). The constraints to model curve fitting are summarized as follows:

The percentages of total initial carbon (C_{C0}) contains the percentages of initial readily, moderately and slowly hydrolysable solid carbon and percentage of initial intermediate solid carbon, as shown in Equation (42).

$$C_{C0} = C_{r0} + C_{m0} + C_{s0} + C_{aq0} \tag{42}$$

The percentages of total final carbon (C_{FC}) contains the percentages of final readily (C_{rfinal}), moderately (C_{mfinal})and slowly (C_{sfinal}) solid carbon and percentage of final intermediate solid carbon ($C_{aqfinal}$), as shown in Equation (43).

$$C_{FC} = C_{rfinal} + C_{mfinal} + C_{sfinal} + C_{aqfinal} \tag{43}$$

For the rate constant, it is assumed that k_{haq} is greater than k_{hr} and the k_{hr} is greater than k_{hm}, as shown in Equation (44). The slow hydrolysis rate constant is equal to zero ($k_{hs} = 0$), which is described by Komilis (2006).

$$0 \leq k_{hm} < k_{hr} < k_{aq} \tag{44}$$

In the lag phase, it is assumed that most kinetic reaction rate and percentage of cumulative C-CO_2 product are equal to zero during composting process, as shown in Equation (45).

$$C_{r\_t}, C_{m\_t}, C_{s\_t}, C_{aq\_t} \text{ and } C_{T\_t} = 0, \text{ for } t \leq c \tag{45}$$

All kinetic parameters are positive value.

3.3 Composting experiment

The biodegradability of PE/starch, PLA, as well as MCE (as a positive control) and PE (as a negative control) were evaluated under controlled aerobic composting condition in the laboratory. According to the biodegradability test, the chemical properties such as pH, total dry solid, volatile solid, moisture content, and C/N ratio of the inoculums at the beginning and the end of the test were recorded as shown in Table 39 and Table 40, respectively.

It was found that the ending pH in MCE and PE/starch is increased from the beginning. Whereas, the pH gradual decreased from 8.51 to 7.85 for PLA and 9.97 to 7.92 for PE. The increase in inoculum pH was also observed in Unmar *et al.* (2008) and Mohee *et al.* (2008). For PLA, inoculum pH is decreased after composting, which agrees with Ghorpade *et al.* (2001). Ghorpade *et al.* (2001) had studied composting of PLA and yard waste and found that lactic acid generation occured in the composting reactor. The inoculum pH of PE becomes lower because of the organic acid formation during the decomposition process. However, the pH of all inoculums, 7.85-8.51, are in the range of favorable conditions for microbial activity (Mohee *et al*., 2008).

The initial volatile solid content of the inoculums are 23.21% for PE, MCE, and PE/starch and 28.24% in PLA. The volatile solid of all inoculums are significantly decreased from the initial value, showing that biodegradation process has occurred.

At the beginning of experiment, the moisture content of the inoculums are recorded as 50.79% for PE, MCE, PE/starch and 47.51% for PLA. A gradual increase in moisture content of all inoculums was observed, implying that microorganisms utilize water during degradation process. Mohee *et al.* (2008) and Unmar *et al.* (2008) mentioned above results that degradation proceeded by microbial activity.

The nitrogen content in the inoculums of MCE, PE/starch and PLA are increased from the initial value, which corresponded to the release of ammonia of plastic samples during decomposition process (Unmar *et al*., 2008). Therefore, a decrease in C/N ratio is observed for inoculums of MCE, PE/starch, and PLA. Whereas, the value of C/N ratio gradual increases from 14.78 to 15.00 for inoculum of PE because of a small nitrogen content of PE. However, the value of C/N ratio of all inoculums are in the range of 11.09-16.78. These indicated that all parameters, such as pH, volatile solid, moisture content, and C/N ratio of the inoculums are under appropriate composting environment.

Additionally, it is interesting to assess the heavy metal limits. Table 43 describes toxic metal analysis of the inoculums after biodegradability testing. Similarly, Not only compost product gives a consistent result with the limit of organic farming in Department of agriculture Extension (2005), but also it does not exceed the 50% of level for The European Committee for Narmalisation (CEN) 13432, as shown in Table 41. This concerns that toxic conditions from test material and inoculums do not occur.

Table 39 Chemical properties of the inoculums before biodegradability testing.

Parameters	inoculums	
	PE, MCE, and PE/starch	PLA
pH	7.97	8.51
Total dry solid, (%)	49.21	52.49
Volatile solid, (%)	23.21	28.24
Moisture, (%)	50.79	47.51
C/N	14.78	16.78

Table 40 Chemical properties of the inoculums after biodegradability testing.

Parameters	inoculums			
	PE	MCE	PE/starch	PLA
pH	7.92	8.33	8.30	7.85
Total dry solid, (%)	49.38	47.21	48.51	50.61
Volatile solid, (%)	20.04	20.70	20.81	18.10
Moisture, (%)	50.62	52.79	51.49	49.39
C/N	15.00	11.09	11.69	11.26

Table 41 Toxic metal analysis of the inoculums after biodegradability testing.

Parameters	inoculums				
	PE	MCE	PE/starch	PLA	Standard
As, (mg/kg)	2.95	2.82	2.86	4.41	< 50[a], 5[b]
Cd, (mg/kg)	0.40	0.30	0.3	0.1	< 5.0[a], 0.5[b]
Cr, (mg/kg)	15.30	15.30	15.4	8.1	< 300[a], 50[b]
Cu, (mg/kg)	30.80	27.70	28.7	66.25	< 500[a], 50[b]
Hg, (mg/kg)	0.068	0.06	0.057	0.041	< 2.0[a], 0.5[b]
Pb, (mg/kg)	9.60	9.40	9.2	4.5	< 200[a], 50[b]
Zn, (mg/kg)	127.30	106.00	124.1	106.6	< 150[b], 150[b]

[a] Department of Agriculture Extension in Thailand (2005)

[b] CEN 13432 (as per EN 13432)

3.4 Model and morphology analysis

The parameters of kinetic model in equation (46) and a set of constraints are determined from the experiment data. A good agreement of analytical data can be observed from the correlation coefficients (R^2) for data fitting from percentage C-CO_2 cumulative over time, as shown in Figure 63 - Figure 65. It is generally significant at the confidence level higher than 0.95. The results of the kinetic study are shown in Table 42. The SEM morphology was also used to evaluate the results before and after biodegradation testing, as shown in Figure 66 - Figure 68. The PE shows minimal degradation after 90 days. The C-CO_2 evolution of PE is 0.56, implying that there is no biodegradation. Figure 66 (a) shows the uniform continuous matrix of PE before biodegradation testing. The observations from the SEM morphology confirms above results because the surface of PE unchanged after biodegradation testing, as shown in Figure 66 (b).

Initial solid carbon in MCE is found as readily, moderately hydrolysable carbon fraction and initial intermediate solid carbon. The readily biodegradation in cellulose occur because of the activity of the cellulose enzyme complex that catalyses the hydrolysis or oxidation of cellulose (Davis, 2003). As the results above, the initial slowly hydrolysable carbon fraction is not presented in cellulose. For C-CO_2 evolution comparison, cellulose produces the highest percentages. The degradation of cellulose is about 94.34% with the best fitting constant value ($R^2 = 0.99$), as shown in Figure 63. The readily hydrolysable carbon hydrolysis rate is 0.3387 day^{-1}, which is the fastest rate of all the material studied. The moderately hydrolysable carbon hydrolysis rate is 0.0227 day^{-1}. Since the growth of microbial activity starts immediately in the MCE curve, so lag phase in the biodegradation curve is not observed. According to the kinetic model calculation, the values of first order readily and moderately hydrolysis rate constant ($k_{hr} \geq 0.06$ and $k_{hm} \leq 0.06$) in MCE is consistent with Komilis (2006). The SEM morphology of MCE can't be observed because the sample disappears after biodegradability test.

Initial solid carbon in PE/starch includes moderately hydrolysable carbon and intermediate solid carbon. The moderately hydrolysable carbon hydrolysis rate is 0.00098 day^{-1}. Therefore, the degradation of PE/starch shows the lowest of 11.5% reduction in total C-CO_2 evolution, as shown in Figure 64. The transportation of water within the hydrophilic polymer from the polymer matrix is occurred after biodegradation testing (Shah *et al.,* 2008). It can be observed that the swelling at the starch granule occurs throughout the surface of PE/starch due to water absorption of the starch granule, as shown in Figure 67 (b). The swelling at the starch granule become more deformation in the hydrophilic polymer (Shah *et al.,* 1995). Swollen granule of the polymer matrix is not occurred in high fraction since almost all surface of PE/starch is unchanged.

Initial solid carbon of PLA also has three types of carbons including readily, moderately hydrolysable carbon, and intermediate solid carbon. The degradation of PLA is about 85.75% with best fitting constant value (R^2 = 0.99). The rates of readily and moderately hydrolysis are equal to 0.025 day^{-1} and 0.0178 day^{-1}, respectively. It presumes that the relation of lag phase to C-CO_2 evolution is closed to zero during composting process. The different behavior is exhibited in PLA. There is microbial activity lag phase observed since C-CO_2 evolution occurs started at day 21st, as shown in Figure 65. Lag time in this stage is relatively closed to the range of 16-18 days that described by composting results. It can be considered that the profiles of biodegradation curve with time shows sigmoidal behavior. The system started by breaking the formation in the solid polymer, then the C mineralization product of the growth phase gradually increases during 28 and 110 day. The stationary phase start after 115 days, indicating that decomposition rate was dropped after growth phase. Figure 68 (a) shows the SEM morphology of PLA. It can be observed smooth surface before biodegradation testing. The SEM morphology confirms the biodegradation of PLA because chain break and the dimension clearly decrease on the surface after biodegradability test, as shown in Figure 68 (b).

The high concentration of moderately hydrolysable carbon in MCE and PLA is 43.04% and 59.80%, respectively. The presence of readily hydrolysis carbon in high fraction indicated a large easily biodegradable (Komilis, 2006) portion in MCE and PLA, which is around 55.49% and 40.17%, respectively. The highest hydrolysis rate of MCE compared to other substrate causes by the higher readily hydrolysis carbon fraction synergize the high microbial activity. The reduction of volatile solid in the compost of MCE shows the microbial activity, which consistent with Mohee *et al*. (2008) and Ummar *et al.* (2008), as shown in Table 62. Moreover, it is probably due to low surface free energy interaction in cellulose, as presented by Mohee *et al*. (2008). It can be mentioned that cellulose has a hydrophilic character and degrade easily by microorganisms (Dourado *et al.,* 1998) and (Mohee *et al.,* 2008).

The high fraction of moderate hydrolysable carbon has been found in PE/starch, which is around 97.74%. As mentioned above, the SEM morphology of PE/starch confirms the results. Due to almost all the surface of PE/starch has the uniform matrix before biodegradation testing, as shown in Figure 67 (a). It can be observed that blending of starch with polyethylene is uniform throughout the substrate. The presence of moderately hydrolysable carbon fraction in high concentration inhibits the microorganisms attacked. Therefore PE/starch gives the low amounts of percentage C-CO_2 evolution.

The low fraction of initial intermediate hydrolysis carbon in PLA is calculated as 0.082% because of the smooth surface and well dried before biodegradation testing, as shown in Figure 68 (a). The high fraction of initial intermediate hydrolysable carbon in both MCE and PE/starch is 1.459% and 2.255% respectively because of low surface free energy and hydrophilic character in MCE and high water absorption at the starch granule in PE/starch.

The first order reaction in series with a flat lag phase model is desirable for MCE, PE/starch and PLA. However, the correlation coefficient for data fitting in PLA is not good for the mineralization rate constant (k_{aq}) at 10^6 day^{-1} as Komilis (2006). It may be indicated that degradable mechanism from lag phase into growth phase of PLA gradually increases (Iovino *et al.,*. 2008), as shown in Figure 65 while degradable mechanism of MCE, and PE/starch starts from growth phase immediately (linear increasing), as shown in Figure 63 and Figure 64, respectively. Therefore, the mineralization rate of PLA is equal to 0.500 day^{-1} while the mineralization rate of MCE and PE/starch are equal to 1.234 day^{-1} and 1.000 day^{-1}, respectively.

A good agreement of analytical data in this kinetic model was observed, since the R^2 values are high, especially in MCE and PLA. However, correlation coefficients (R^2) for data fitting in the PE/starch are quite close to significant level in prediction. Moreover, the results presented in the work can be used to estimate retention time of aerobic biodegradation of the biodegradable plastics.

Table 42 Kinetic model parameters and coefficients of determination (R^2).

Parameters	PE	MCE	PE/starch	PLA
C_{aq0}, (%)	–	1.459	2.256	0.022
C_{r0}, (%)	–	55.498	–	40.174
C_{m0}, (%)	–	43.043	97.744	59.804
C_{s0}, (%)	–	–	–	–
k_{aq}, (day^{-1})	–	1.23451	1.00000	0.50000
k_{hr}, (day^{-1})	–	0.33872	–	0.02500
k_{hm}, (day^{-1})	–	0.02275	0.00098	0.01786
k_{hs}, (day^{-1})	–	–	–	–
c, (day)	–	0	0	21.37
Biodegradability, (%)	0.56	94.34	11.50	85.75
R^2	–	0.9928	0.9496	0.9969

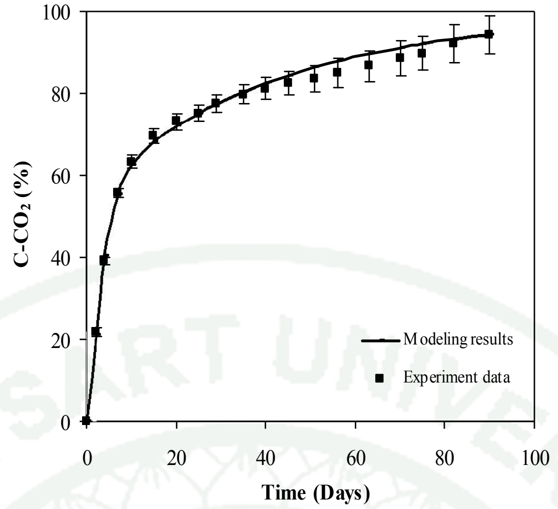


Figure 63 Kinetic of percentage CO_2 evolutions during degradation of MCE (the bar is standard error).

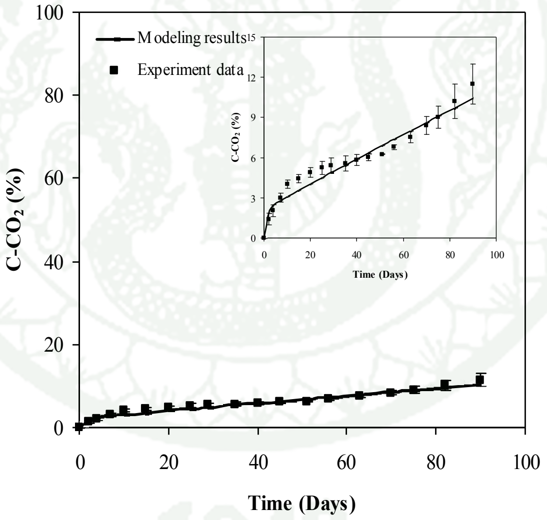


Figure 64 Kinetic of percentage CO_2 evolutions during degradation of PE/starch (the bar is standard error).

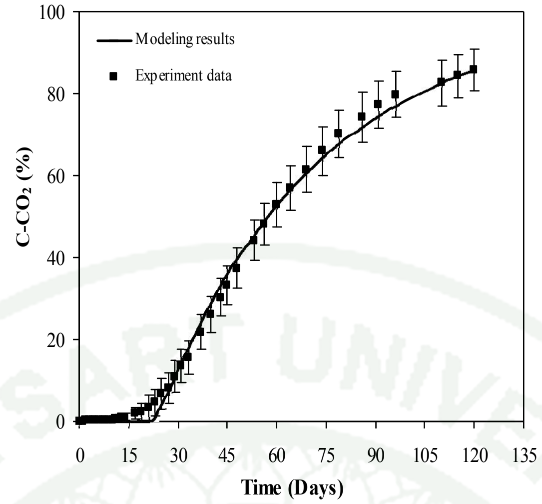
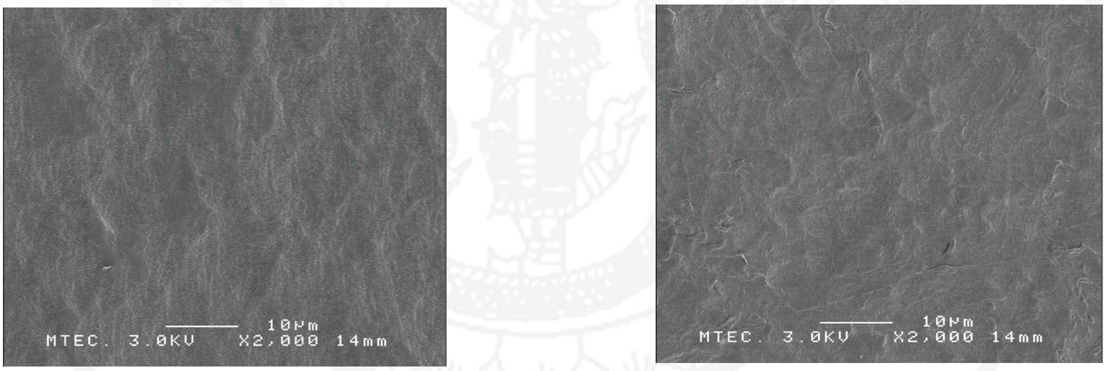


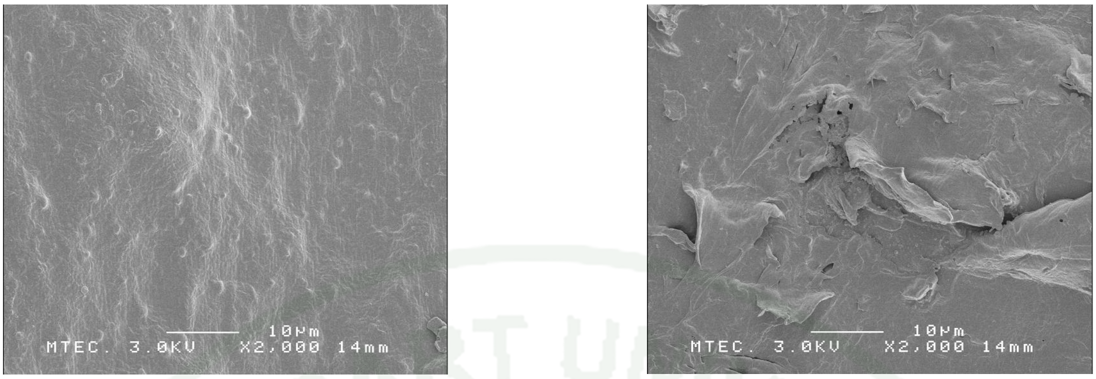
Figure 65 Kinetic of percentage CO_2 evolutions during degradation of PLA (the bar is standard error).



(a)

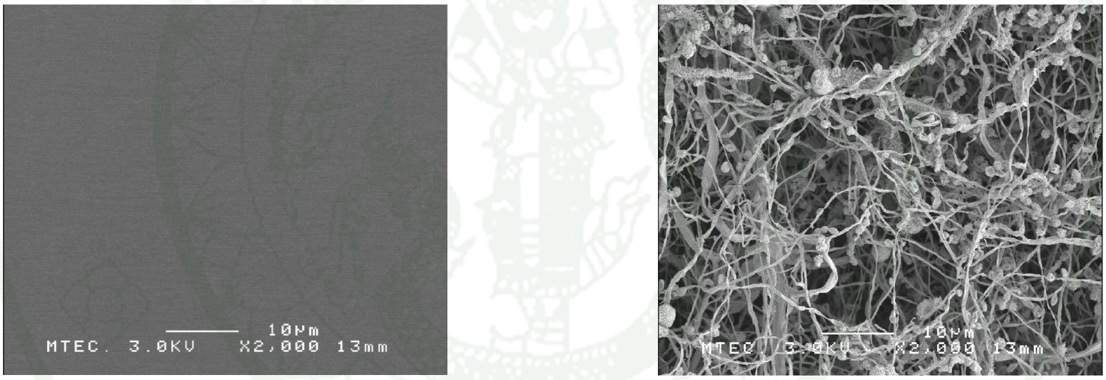
(b)

Figure 66 SEM micrographs of surface of PE before (a) and after biodegradation testing (b) after 90 days.



(a) (b)

Figure 67 SEM micrographs of surface of PE/starch before (a) and after biodegradation testing (b) after 90 days.



(a) (b)

Figure 68 SEM micrographs of surface of PLA before (a) and after biodegradation testing (b) after 120 days.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results can be concluded as follows:

1. Life cycle inventory data of two types of packages obtained from this study: firstly, two types of trays made from PLA and PS; secondly, three types of garbage bags made from PE/starch, PE/TDPA, and conventional PE.

2. Life cycle energy consumption and environmental impacts of two types of packages obtained from this study. The results of energy used and environmental impact of trays and garbage bags are summarized as follows:

2.1 Energy consumption and environmental impact (Cradle-to-gate)

1) PLA and PS trays

It is found that energy consumption of PLA trays is higher than those PS trays of 1.88 times. The highest portion of energy consumption of PLA trays come from electricity and natural gas in PLA production whereas PS trays come from crude oil and natural gas extraction.

The environmental impact assessment, PLA trays generated 2.57 times higher environmental impact than PS trays. This is due to the environmental impact score of PLA trays are from PLA production and corn plantation approximately 50.2% and 28.9%, respectively. The reason is due to the largest contribution to abiotic depletion, marine aquatic ecotoxicity, and global warming, respectively. For PS trays, the causes of total environmental impact score obtained from crude oil and natural gas extraction of 74.1% and 11.2%, respectively. The main environmental impacts for PS trays are also dominated by abiotic depletion, marine aquatic ecotoxicity and global warming, respectively.

2) PE/starch, PE/TDPA, and PE garbage bags

It is found that the highest energy consumption of PE/starch is higher than that PE/TDPA, and PE garbage bag of 5.4 times, and 6.9 times, respectively. The main contribution comes from raw material extraction, followed by materials preparation (ethylene) and garbage bag production. Additionally, the high consumption of virgin material and high weight of package in PE/starch is the main cause of energy used that is required to 500,000 liter of garbage bags.

The results obtain from the impact assessment, the total environmental impact of PE/starch is higher that PE/TDPA, and PE garbage bags, which are 6.3 and 7.1 times, respectively. The total environmental impact score of PE/starch garbage bags are mostly from crude oil and natural gas extraction and garbage bag production, approximately 56.4-71.4% and 11.7-28.2%, respectively. This is due to it consumes virgin materials for HDPE and LDPE pellets. Whereas, PE garbage bags generate the lowest environmental impact score because they consume recycling HDPE and LDPE pellets of 29.9% and 19.4%, respectively.

2.2 Life cycle energy consumption and environmental impact with waste management (Cradle-to-grave)

1) PLA and PS trays

It is found that incineration with energy recovery is suitable with management of PS trays. For PLA trays, it is found that composting is the best option. In addition, PLA trays with landfill with energy recovery from methane collection also show a good result, followed by incineration and heat recovery. The worst scenario, incineration contributes the highest energy consumption for both PLA and PS trays. However, the life cycle energy consumption and environmental impact of PLA together with composting, landfill with energy recovery from methane collection, or incineration and heat recovery are higher than PS trays with incineration with heat recovery. As above results, the reason is higher weight of material consumption resulting in high portion of energy and environmental impact in production stage. The worst scenario for PLA trays is option 1, where plastics waste is disposed of in landfill of 90% and incineration of 10%. The main causes come from high amount of landfill gas emission of PLA and high amount of combustion emission from incineration for PLA. Whereas, PS trays are disposed by incineration contributes the highest environmental impact due to high amount of combustion emission.

2) PE/starch, PE/TDPA, and PE garbage bags

The life cycle energy consumption and environmental impact of degradable garbage bags together with incineration and heat recovery give the best results, followed by landfill with energy recovery from methane collection**.** It is found that the life cycle energy consumption and environmental impact of degradable garbage bags namely PE/starch and PE/TDPA together with incineration and heat recovery is higher than conventional PE garbage bag with incineration with heat recovery. The reason is higher weight of material consumption resulting in high portion of energy and environmental impact in production stage.

3. The kinetics model was based on first order reaction in series with a flat lag phase.

4. The biodegradable kinetics of PE, MCE, PE/starch and PLA under controlled composting condition can be concluded as follows:

4.1 The biodegradability testing of the testing samples are done under appropriate aerobic composting conditions according to ISO 14855-99

4.2 Initial solid carbon in MCE and PLA consists of readily, moderately hydrolysable carbon fraction and intermediate solid carbon. While initial solid carbon in PE/starch consists of moderately hydrolysable carbon fraction and intermediate solid carbon.

4.3 The fraction of initial intermediate hydrolysable carbon for PLA is 0.082%. While initial intermediate hydrolysable carbon for PE/starch and MCE are 1.459% and 2.256%, respectively.

4.4 The high concentration of readily hydrolysable carbon in MCE and PLA are 55.49% and 40.17%, respectively, which gives the high percentage of C-CO_2 evolution by 94.34% and 85.75%, respectively. The moderately hydrolysable carbon in MCE and PLA are 43.04% and 59.80%, respectively. Corresponding to rate constant of MCE and PLA, the mineralization rate are equal to 1.234 day^{-1} and 0.500 day^{-1}, respectively, readily hydrolysis rate are equal to 0.338 day^{-1}and 0.025 day^{-1}, respectively and moderately hydrolysis rate are equal to 0.022 day^{-1}and 0.017 day^{-1} , respectively.

4.5 The high concentration of moderately hydrolysable carbon in PE/starch is 97.74%, which gives the low percentage of C-CO_2 evolution by 11.50%. Corresponding to rate constant of PE/starch, the mineralization rate is equal to 1.000 day^{-1}, the moderately hydrolysis rate is equal to 0.00098 day^{-1}.

Recommendations

The result of this research could be used to provide information for decision making of the government, industries and consumers. It can be concluded as follows:

1) The end of life management of biodegradable packages is a very crucial step and has the influence on environmental impact. Composting is the most environmental preferred choice for end of life management of biodegradable plastics. Hence, the use of biodegradable packages as an end of life management should be promoted in Thailand.

2) From the results of life cycle energy consumption and environmental impacts of PE/starch and PE/TDPA garbage bags obtained from this study. It is recommended that PE/starch and PE/TDPA are not suitable to produce garbage bags because of the very low degradability which are only, 8.18% and 3.23% respectively under natural landfill and 11.50% and 0.02% respectively under composting condition.

There are a few important points needed to be further studied. Those further studies are as follows:

1) In this research, the starch and PLA blends at the ratio of 0/100 and 100/0 were studied. So, future study to assess the environmental impacts of starch and PLA blends, at the ratio of 70/30, 50/50, and 30/70 would provide useful information for tray application or other applications, e.g. drinking straw, cup, spoon, and fork.

2) It would be useful to assess biodegradable kinetic of starch and PLA blend both under composting and landfilling conditions. As a result, the lag time of starch and PLA blend may be less than 100% PLA and the degradability would be achieved in short time. This is because of the hydrophilic character and easily degradability by microorganism of the starch.

3) Additional to PS and PE in this study, other widely used conventional plastics in packaging applications such as polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) should be investigated as well.

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APPENDICES

Appendix A

Element analysis

According to energy content of plastic waste, incineration of 1 kg plastic waste was calculated from the value of proximate analysis and element analysis of plastics material (Pichtel, 2005) as shown in Equation A1 and Table A1.

$$\mathrm{HHV(MJ/kg)} = 0.339(\mathrm{C}) + 1.44(\mathrm{H}) - 0.139(\mathrm{O}) + 0.105(\mathrm{S}) \qquad (1)$$

where, HHV is higher heating value (MJ/kg).

Appendix Table A1 Element analysis of plastics material.

Type	Unit
Carbon (C)	%
Hydrogen (H)	%
Oxygen (O)	%
Other: Nitrogen (N), Sulfur (S)	%

Source: Pichtel (2005)

Appendix B

LCI data of PLA trays

Appendix Table B1 LCI data of corn plantation (1,000 kg of corn).

Item	Amount	Unit
Mass/Energy input		
Fertilizer-N	48.30	kg
Fertilizer-P	75.56	kg
Fertilizer-K	18.44	kg
Atrazine	0.20	kg
Diesel	1,060.50	MJ
Corn seeding	3.65	kg
CO_2 absorption	2,095.24	kg
Land used	158.73	m^2
Mass/Energy output		
Corn	1,000	kg
Air emissions		
Ammonia	2.73	kg
Nitrogen oxide	0.051	kg
Dinitrogen monoxide	0.205	kg
Solid waste		
Nitrate	23.89	kg
Total Phosphorus	0.025	kg
Antrazine	0.0894	kg

Source: SimaPro 7.0

Appendix Table B2 Distance of material transportation for PLA trays.

Types	Source- Destination	Transport by	Distance (km)
Seed	Nebraska U.S.- Nebraska U.S.	Truck	20*
Corn	Nebraska U.S.- Nebraska U.S.	Truck	20*
PLA	Nebraska U.S.- New York's Port	Truck	2,431
PLA	New York's Port- Thailand's Port	Shipment	15,864
PLA	Thailand's Port- Rayong Province	Truck	_
PLA	Rayong Province- Bangkok/Nakornpatom Province	Truck	199.79
PE Bags	Average from Bangkok/Nakornpatom Province	Truck	20*
PLA Tray	Tray Factory- User (same province)	Truck	20*

Note: * 20 km is assumed within the same province

Appendix Table B3 LCI data of PLA tray production with recycling process.

Item	Amount	Unit
Mass/Energy input		
PLA	13.686	kg
PLA (recycle)	2.258	kg
Electricity	27.237	kg
PE Bags	0.0730	kg
Glue	1.23E-03	kg
Mass/Energy output		
PLA trays	13.59	kg
Solid waste		
Waste (PLA)	0.2496	kg
Scrap (PLA)	2.4839	kg

Appendix Table B4 Distance of corn to PLA production in Thailand of PLA-improved 2.

Province	Capacity year 2007 (ton/yr)	Distance (km.)
Nakhon Sawan	290,593	486.12
Phetchabun	614,168	412.92
Loie	123,043	311.61
Nakhon Ratchasima	458,084	283.94
Lopburi	286,353	456.71
Sa Kaeo	160,632	438.6
Total capacity	1,932,873	–
Average distance (km)	$\frac{\sum capacity(ton/yr) \times distance(km)}{Total - capacity(ton/yr)}$	362.27

Appendix Table B5 Distance of material transportation for PLA-improved 2.

Types	Source- Destination	Transport by	Distance (km)
Seed	-	Truck	20*
Corn	-	Truck	20*
PLA	Corn – Rayong Province	Truck	362.27
PE Bags	Bangkok/Nakornpatom Province – Rayong Province	Truck	199.79
PLA Tray	Tray Factory- User (same province)	Truck	20*

Note: * 20 km is assumed within the same province

Appendix Table B6 LCI data of PLA trays production in the case of PLA-improved 3 and PLA-improved 4 (420 liters of PLA trays).

Item	PLA-improved 3	PLA-improved 4	Unit
Mass/Energy input			
PLA	15.94	8.86	kg
PLA (recycle)	–	–	kg
Electricity	27.837	8.858	kg
PE Bags	0.0083	0.0046	kg
Glue	1.11E-03	6.2E-04	kg
Mass/Energy output			
PLA trays	13.59	8.86	kg
Solid waste			
Waste (PLA)	2.3544	1.308	kg
Scrap (PLA)	–	–	kg

Appendix Table B7 LCI of PLA production with biomass feedstock (420 liters of PLA trays).

Item	Amount	Unit
Mass/Energy input		
Corn and residue	1,656.80	kg
Water, cooling, surface	7,850.00	kg
Water (irrigation)	32,100.00	kg
Electricity	3,611.12	kWh
Natural gas	3,931.06	kg
Mass/Energy output		
PLA	1,000	kg
Solid waste (Turn to energy)		
Residue (Corn)	98.10	kg
Residue (Lactic acid)	50.00	Kg
Residue (Dextrose)	90.00	kg
Emission to water		
Waste water	32,100.0	kg
Cooling water	7,850.0	kg
Final waste flow		
Waste unspecified	418.70	kg

Appendix C

LCI data of PS trays

Appendix Table C1 LCI data of crude oil exploration (1,000 kg of crude oil).

Mass/Energy input	Amount	Unit
Gas, petroleum, in ground	5.50	m^3
Oil, crude, in ground	1,000	kg
Chemical inorganic	0.12	kg
Chemical organic	0.09	kg
Diesel	0.37	GJ
Petroleum gas blow off	3.0	m^3
Petroleum gas blow flaring	41.6	m^3
Petroleum gas in gas turbine offshore	0.7510	GJ
Residual oil in Boiler 1 MW	0.2400	GJ
Mass/Energy output	Amount	Unit
Crude oil	1,000	kg
Emission to Air		
Methane	2.0	kg
Carbon dioxide	0.0770	kg
Methane (Halon-130)	0.0002	kg
Helium	0.0060	kg
NMVOC	6.6	kg
Emission to Water		
Chloride	50.0	kg
Calcium	3.0	kg
Sodium	30.0	kg

Source: SimaPro 7.0

Appendix Table C2 LCI data of natural gas offshore (1 m^3 of natural gas).

Mass/Energy input	Amount	Unit
Resources		
Gas, natural, in ground	1.000E+00	m3
Water, salt, ocean	1.154E-06	m3
Water, salt, sole	2.985E-06	m3
Materials/fuels		
Chemicals inorganic	1.338E-06	kg
Chemicals organic	1.017E-06	kg
Ethylene glycol	2.183E-05	kg
Methanol, at regional storage	3.525E-05	kg
Electricity, medium voltage	1.162E-02	kWh
Sweet gas, burned in gas turbine	4.496E-03	m3
Plant offshore, natural gas	3.612E-11	p
Diesel, burned in diesel-electric generating set	7.983E-03	MJ
Well for exploration and production	7.003E-06	m
Transport, lorry 32t	5.868E-06	tkm
Transport, freight, rail	4.230E-06	tkm
Mass/Energy output	Amount	Unit
Emissions to air		
Carbon dioxide, fossil	1.779E-03	kg
Carbon monoxide, fossil	3.193E-05	kg
Heat, waste	4.195E-02	MJ
Hydrocarbons, aliphatic, alkanes	4.482E-05	kg
Hydrocarbons, aromatic	2.339E-05	kg
Mercury	1.499E-10	kg
Methane, chlorodifluoro-, HCFC-22	7.983E-08	kg
Methane, dichlorodifluoro-, CFC-12	7.983E-10	kg
Methane, fossil	1.898E-04	kg
Nitrogen oxides	5.749E-07	kg
Radon-222	5.231E-05	kBq
Sulfur dioxide	1.085E-06	kg

Appendix Table C2 (Continued).

Mass/Energy output	Amount	Unit
Emissions to water		
AOX, Adsorbable Organic Halogen as Cl	5.161E-13	kg
BOD5, Biological Oxygen Demand	7.338E-06	kg
Cadmium, ion	3.081E-11	kg
COD, Chemical Oxygen Demand	7.338E-06	kg
DOC, Dissolved Organic Carbon	2.080E-06	kg
Lead	2.080E-09	kg
Mercury	7.704E-12	kg
Methanol	1.036E-05	kg
Nickel, ion	2.311E-10	kg
Nitrogen	3.871E-11	kg
Oils, unspecified	5.007E-08	kg
Sulfur	1.340E-10	kg
TOC, Total Organic Carbon	2.080E-06	kg
Triethylene glycol	7.770E-06	kg
Zinc, ion	7.049E-09	kg
Waste to treatment		
Antifreezer liquid, 51.8% water, to hazardous waste incineration	8.543E-08	kg
Emulsion paint remains, 0% water, to hazardous waste incineration	3.760E-07	kg
Used mineral oil, 10% water, to hazardous waste incineration		kg
Wood untreated, 20% water, to municipal incineration	6.064E-06	kg
Municipal solid waste, 22.9% water, to sanitary landfill	2.787E-05	kg
Hazardous waste, 0% water, to underground deposit	3.767E-05	kg

Source: SimaPro 7.0

Appendix Table C3 LCI data of GPPS pellets production (1,000 kg of GPPS pellets).

Item	Amount	Unit
Mass/Energy input		
Styrene monomer	839.20	kg
Ethylbenzene	85.90	kg
Peroxide	30.30	kg
Mineral oil	55.60	kg
PE bags	6.120	kg
Fuel oil	0.141	Liter
Electricity	390.10	kWh
Water	5,949	kg
Mass/Energy output		
GPPS pellets	1,000	kg
Air emissions		
TSP	8.52E-02	kg
NO_2	7.47E-03	kg
CO	9.47E-04	kg
Antinony (Sb)	5.87E-01	kg
CO_2	2.85E-01	kg
SO_2	1.00E-06	kg
VOC	4.08E-07	kg
Solid waste		
Residue waste	1.50E+00	kg
Chemical waste	3.00E+00	kg
Polystyrene waste	4.52E+00	kg
PE bags	4.40E+00	kg
Others waste		
Steam	5.94E+03	kg
Tar	2.08E+00	kg

Source: Paoluglam (2005)

Appendix Table C4 LCI data of HIPS pellets production
(1,000 kg of HIPS pellets).

Item	Amount	Unit
Mass/Energy input		
Styrene monomer	840.00	kg
Ethylbenzene	30.00	kg
Peroxide	58.00	kg
Mineral oil	28.00	kg
Polybutadiene rubber	120.00	kg
PE bags	6.120	kg
Fuel oil	0.050	Liter
Electricity	2,145	kWh
Water	5,949	kg
Mass/Energy output		
GPPS pellets	1,000	kg
Air emissions		
TSP	2.45E-01	kg
NO_2	1.28E-02	kg
CO	2.56E-03	kg
Antinony (Sb)	1.60E+00	kg
CO_2	2.85E-01	kg
SO_2	1.00E-06	kg
VOC	4.08E-07	kg
Solid waste		
Residue waste	8.60E+00	kg
Chemical waste	4.98E+00	kg
Plastics waste	4.95E+01	kg
PE bags	4.40E+00	kg
Others waste		
Steam	5.94E+03	kg
Tar	2.08E+00	kg

Source: Paoluglam (2005)

Appendix Table C5 Details of crude oil transportation to Thailand.

Source	Destination	Transport	%	Distance (km)
Middle East	Rayong	Ship	80.58	8,884
Far east Asia	Rayong	Ship	5.62	856.67
Domestic	Rayong	Ship	9.73	810.00
(Erawan/Lamkrabue)	Rayong	Rail	4.07	483.76

Source: Karom (2009)

Appendix Table C6 Details of natural gas transportation to Thailand.

Source	Destination	Transport	%	Distance (km)
Erawan	Rayong	Pipeline	44.48	415
Erawan (parallel pipeline)	Rayong	Pipeline	55.52	418

Source: Karom (2009)

Appendix Table C7 Distance of material transportation for GPPS and HIPS pellets production.

Type	Transport by	Distance (km)
Styrene monomer	Pipe	2.00
Ethyl benzene	Shipment	2.00
White mineral oil	Shipment	2,703.70
Polybutadiene rubber	Shipment	15,864.91
Peroxide	Shipment	15,864.91
PE Bags	Truck	190.65

Source: Paoluglam (2005)

Appendix Table C8 Distance of GPPS and HIPS pellets from Rayong province to PS tray factories in Thailand.

Province	Distance (km.)
Chachoensao	130.25
Samutsakhon	205.11
Nakhonpathom	230.26
Chonburi	93.01
Lopburi	300.73
Pathumthani	198.54
Nonthaburi	187.76
Bangkok	169.31
Samutprakan	191.26
Average distance (km)	198.90

Source: Thai Plastics Foam Recycling Industries Association (2009)

Appendix Table C9 Distance of material transportation to PS tray factories in Thailand.

Types	Source (Province)	Transport by	Distance (km)
Calcium	Saraburi	Truck	116.05
Nitrogen	Saraburi	Truck	116.05
Talcum	Saraburi	Truck	116.05
Butane	Rayong	Truck	189.58
PE Bags	Bangkok/Nakornpatom	Truck	66.47

Source: Department of Highway

Appendix D

LCI data garbage bags

Appendix Table D1 LCI data of cassava cultivation (1,000 kg.).

Item	Amount	Unit
Mass/Energy input		
Cassava root	43.125	kg
Cassava hull	1,076.00	kg
Poultry manure	258.00	kg
N-fertilizer	1.249	kg
N-fertilizer	0.700	kg
K-fertilizer	1.336	kg
Diesel	2.475	kg
Zinc	0.086	kg
Alachlor	0.096	kg
Paraquat	0.150	kg
Glyphosate	0.292	kg
Land used	436.205	m^3
Mass/Energy output		
Cassava root	1,000.00	kg
Trunk	436.00	kg
Cassava waste	555.05	
Air emissions		
Carbon dioxide	8.315	kg
Nitrogen oxide	0.171	m3
Sulfur dioxide	0.011	
Nitrous oxide	0.044	
Ammonia	0.264	kg
VOC	0.058	kg

Source: Khongsiri (2009)

Appendix Table D2 LCI data of cassava starch production (1,000 kg.).

Item	Amount	Unit
Mass/Energy input		
Cassava root	43.125	kg
Sulphur	1,076.00	kg
Water	258.00	kg
Heavy oil	1.249	kg
Electricity	0.700	kg
Mass/Energy output		
Cassava starch	1,000.00	kg
Cassava hull	135.994	kg
Trunk	68.224	kg
Cassava waste	1,457.27	kg
Sand	20	kg
Watse		
Starch waste	121.582	kg
Air emissions		
Carbon dioxide	61.53	kg
Nitrogen oxide	0.252	kg
Sulfur oxide	0.331	kg
Steam	265.131	kg
Water emissions		kg
Waste water	13,664.654	kg
BOD	127.570	kg
COD	265.131	kg
Total nitrogen	6.503	kg
Total phosphorus	0.400	kg
Suspend solid	90.048	kg

Source: Khongsiri (2009)

Appendix Table D3 Distance of material transportation to PE (HDPE/LDPE/LLDPE) factories in Thailand.

Types	Source (Province)	Transport by	Distance (km)
HDPE/LDPE/ LLDPE			
Ethylene	Rayong	Pipeline	2
Propane	Rayong	Pipeline	2
Peroxide	_	Shipment	882.09
Isoparaffin	Rayong	Pipeline	2
Butane	Rayong	Pipeline	2
Hexane	Rayong	Pipeline	2
Octane	Rayong	Pipeline	2
Pentane	Rayong	Pipeline	2

Source: Department of Highway and Paoluglam (2005)

Appendix Table D4 Distance of material transportation (HDPE, LDPE and LLDPE) to garbage bag factory.

Types	Source (Province)	Transport by	Distance (km)
HDPE	Rayong	Truck	211.82
LDPE	Rayong	Truck	211.82
LLDPE	Rayong	Truck	211.82

Source: Department of Highway

Appendix Table D5 Distance of material transportation for cassava root to cassava planting, cassava to cassava starch and cassava starch to garbage bag factory.

Types	Transport by	Distance (km)
Cassava root	Truck	20.0
Cassava	Truck	20.7
Cassava starch	Truck	294.14

Source: Department of Highway

Appendix Table D6 Distance of material transportation for TDPA additive to garbage bag factory.

Source	Transport by	Distance (km)
Neawzeland/Australia	Shipment	7,842.41
Thailand's Port	Truck	47.42

Source: Department of Highway and Mapcrow (2009)

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