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Financial and Economic Viability of Bioplastic Production in Thailand

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March, 2014

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FINANCIAL AND ECONOMIC VIABILITY OF BIOPLASTIC PRODUCTION IN THAILAND

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EXECUTIVE SUMMARY

Across the world, environmental concerns and the challenge of sustainable development are the driving forces behind the conservation of finite petroleum resources. Perhaps most significantly, climate change, which is mainly caused by greenhouse gas (GHG) emissions from the combustion of fossil fuels, has become a significant global environmental issue and a major reason why the use of petroleum reserves must be reduced.

One of the key consumers of petroleum is the plastics industry. The discovery of petroleum-based plastics was a quantum leap in the evolution of material technology. However, it led to the widespread exploitation of petroleum as a raw material for plastic production. This has now been going on for many decades. It is evident that the whole life cycle of petroleum-based plastic production has an adverse impact on non-renewable resources and is the cause of various types of environmental pollution. As a result, many attempts have been made to reduce the impact of the various types of petroleum-based plastics throughout their life cycles. One potential solution that is gaining significant interest is the production of bioplastics, or biodegradable plastics.

Bioplastics are plastics derived from natural and renewable feedstock. They have been recognized as a new wave in green industrial production. The comparative advantage of bioplastics over petroleum-based plastics is the fact that they are renewable, biodegradable and potentially sustainable. Thus, bioplastics are thought to offer a more environmentally friendly option than petroleum-based plastics.

Many kinds of bioplastics have been developed, such as starch plastics, polylactic acid (PLA), and polyhydroxyalkanoate (PHA). Among these bioplastics, PLA is of particular interest to Thailand. PLA is a plastic produced via the polymerization of lactic acid. This, in turn, is derived from agricultural products such as starch and sugar that are found abundantly in Thailand. Indeed, Thailand is the world's largest exporter of dried cassava (one possible PLA feedstock), with an annual production capacity of 30 million tonnes.

The cost of cassava production in Thailand is lower than it is in many other countries. This fact means that Thailand has great potential to be a supplier of lactic acid monomer or even to be a PLA production base. To capitalize on this, the Thai government has established the National Innovative Agency (NIA) as a national focal point for the development of the country's bioplastic industry. It has also launched a five-year National Roadmap for Bioplastic Production (2008-2012), which aims to prepare and strengthen the Thai bioplastic industry and its supply chain. The roadmap action plan requires a lot of research and development work to be done to provide a database of supporting information. However, current research mostly deals with the financial analysis of bioplastic production. No research has been done on the indirect costs and benefits of bioplastic production, including its environmental aspects. To support the development and implementation of the National Roadmap, such an economic analysis of bioplastic production is urgently required.

To help fill this information gap, this research analyzes the net social benefits of switching from petroleum-based plastic to bioplastic. It does this using the cost-benefit analysis approach. Its outputs and outcomes will be of use to all relevant stakeholders, in both the government, and the private and social sectors.

The costs and benefits of PLA production are compared with the costs and benefits of high-density polyethylene (HDPE) production, a common petroleum-based plastic. The research looks at the costs of PLA production in two scenarios: 1) the production of PLA resin from cassava root, and 2) the production of PLA resin from cassava starch.

The cost of PLA production comprises of investment costs, direct production costs and indirect environmental costs. The total costs of PLA production calculated for Scenario 1 (cassava root to PLA resin) and Scenario 2 (cassava starch to PLA resin) were USD 2.71 and USD 2.82 per kilogram of PLA, respectively.

The benefits of PLA production include the sale of the by-product from starch production and the value of the carbon embedded in cassava. The net benefits of PLA production for Scenario 1 were USD 3.23/kg of PLA; this was 6.8 times larger than the benefits obtained from HDPE production. However, the net benefits of PLA production for Scenario 2 were only USD 0.18/kg of PLA; this was 2.5 times lower than the benefits obtained from HDPE production.

Because it best reflects the benefits that would accrue to an investor in PLA production, Scenario 2 was selected as the status quo for the calculation of net present values (NPV). The NPVs were calculated for three potential future circumstances: 1) if there are changes in benefits due to PLA price developments; 2) if there are changes in costs due to technological development; and 3) a combination of 1 and 2. Only 1 gave a negative NPV while the rest gave positive NPVs. A sensitivity analysis was conducted based on the variation of real discount rates. The following values were used: 1.29 % (status quo), 3.29%, and 5.29%. All results were insensitive to the increase of real discount rates.

Interestingly, the environmental cost of PLA production was twice that of HDPE production. This was due to the large emissions of GHGs that PLA production caused. These emissions were mainly caused by the electricity and fuel oil used. Methane emissions from wastewater treatment using aerated lagoon were also a major source of GHG. HDPE production caused fewer environmental burdens due to its better energy efficiency, its better air pollution treatment process and the fact that there was less organic content in its wastewater. This finding shows that there are large opportunities for improvements in the PLA production process.

The research therefore recommends policies that focus on the PLA production process and which champion energy efficiency improvements, the implementation of clean technology, and the utilization of the biomass waste and biogas produced from the wastewater treatment process as an energy source. For example, tax exemptions or reductions (and/or soft loans) should be provided as incentives to starch and sugar producers who implement clean technology program and biogas recovery systems. Tax exemptions for new imported equipment should also be made available to all bioplastic producers and suppliers who enroll in an energy efficiency improvement program. In addition, a carbon credit enrollment program should be established for the bioplastics industry to reduce GHG emissions. Supplementary payments should also be introduced for electricity produced from the methane recovered during wastewater treatment. Finally, pollution control measures (coupled with the abovementioned supportive policies) should be effectively implemented to reduce the negative environmental impact of PLA production.

In October 2010, Thailand launched the law of Fiscal Measures for the Environment. The law includes measures such as environmental taxes, product taxes, pollution treatment fees, and emission permits. These measures can be applied to relevant stakeholders in the PLA production chain in order to encourage plant owners to use more environment-friendly technology. Even though this is only a first step for advanced environmental protection in Thailand, it shows that the Thai society has begun to pay more attention to the environment.

1.0 INTRODUCTION

1.0 The Plastics Industry in Thailand

Thailand's plastic industry has been totally integrated into the petrochemical industry's complete production cycle (from feedstocks to downstream) since the industry began in 1980. In the petrochemical industry's production chain, there are three main industrial steps, namely upstream, intermediate and downstream. These steps produce monomers, intermediates, and polymers that are consumed as raw materials in the plastic industry. In Figure 1, the products in each step are exhibited to show the holistic nature of Thailand petrochemical industry.

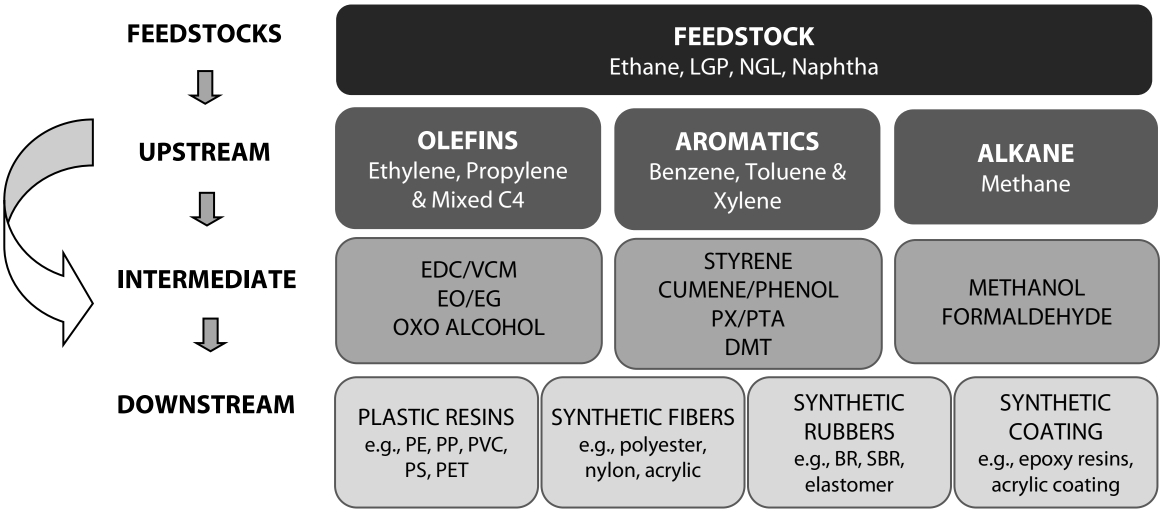

Figure 1. Petrochemical chain in Thailand

Thailand's plastic resin industry accounts for 4% (NIA 2008) of world production. Its annual production in 2003 amounted to 6.38 million tonnes, which exceeded domestic demand by 38.7%. The total production of Thailand's petrochemical industry is ranked 8th in the world, but 1st in Southeast Asia. Accordingly, Thailand is an exporter of plastic resin to the world market.

This research focuses on the plastic products industry, which utilizes plastic resin as its raw material. Through the processing of plastic resin, it produces many consumer products such as packaging, automotive parts, appliances, and textiles. Thailand's plastic product facilities are mainly medium- and small-sized. There are almost 4,300 plastic product factories in the country, which make approximately 3.91 million tonnes of plastic products per year. The most important products are films, foil/tape, synthetic fibers, and woven bags. The most important markets for these products are Japan, USA, Hong Kong, the United Kingdom, Australia, and other Asian countries.

1.1 National Policy for Bioplastic Production in Thailand

At present, the development of bioplastic production in Thailand is at an embryonic stage when compared to the production of fossil-fuel-based plastic. It has therefore been necessary to construct a national road map to accelerate the development of bioplastic production in the country.

According to the National Subcommittee on Economic Restructuring, the development of bioplastics was included in Thailand's economic restructuring plans (under "New Wave Industries") in January 2006. As a result, the National Innovation Agency (NIA 2008) was appointed as the focal point for the development of a bioplastic National Roadmap in February 2006. Subsequently, a five-year National Roadmap for bioplastic production was finalized in 2008.

There are four strategies addressed in the roadmap. These are as follows:

1. ***Ensuring a sufficient supply of biomass feedstock.*** The objective of this strategy is to ensure that there are sufficient biomass raw materials for both the bioplastic industry and for food consumption and that these are of a high enough quality. It also aims to ensure that starch-crop productivity is improved to prevent various problems such as crop shortages and eco-system imbalance.

2. ***Accelerating technology development and technology cooperation.*** This strategy aims to develop local research and development capabilities in order to initiate innovation, capitalize on technology transferred from overseas, and advance domestic technological progress.

3. ***Building industry and innovative business.*** This strategy aims to encourage investment in bioplastic industries and businesses at all steps of the petrochemical production chain (upstream, midstream, and downstream), at the international, national, and local business levels.

4. ***Establishment of a support infrastructure.*** This strategy aims to establish a support infrastructure to facilitate the development of the bioplastic industry in Thailand. Elements of this infrastructure include industrial standards, testing laboratories, certifying bodies for bioplastic products, and an enhancement of the public awareness of bioplastic.

The expected consequences of the implementation of the roadmap are outlined in Table 1.

Table 1. Expected consequences of the National Bioplastic Roadmap

Aspect	Expected consequences
1. Economic, Industrial and Agricultural	Thailand becomes a bioplastic production hub for the international market. Thailand penetrates into the global bioplastic market and takes an appreciable share of this market. Significant value added to agricultural raw materials.
2. Technological	Through technology transfer and local research and development, Thailand acquires important bioplastic intellectual property and integrates foreign technology with local bioplastic research.
3. Environmental	The public awareness of bioplastic products and their use is raised. The environmental burden of plastic waste and plastic production is lowered.
4. Policy	Policies, frameworks and measuring tools are developed that support and incentivize investment in the bioplastic industry.

1.2 Research Problems

Since petroleum-based plastic was first commercialized in the late 18th century, it has been widely utilized for various purposes such as clothes, containers, and packaging. As a result, it has become one of the most important and widespread consumer products. However, petroleum-based plastic does not only provide advantages but also has a range of negative consequences.

- Firstly, because its feedstocks are derived from non-renewable petroleum products, its manufacture depletes finite fossil fuel reserves.

- Next, the production of petroleum-based plastic generates carbon dioxide (CO_2), the most significant GHG. As is widely known, an increase in the quantity of GHG in the earth's atmosphere results in climate change or global warming. This is, arguably, the most significant current environmental issue facing the planet. According to the International Energy Agency (IEA 2008), the global chemical and petrochemical industry emitted around 800 Mt of CO_2 in 2005.

- Last but not least, petroleum-based plastics require a few hundred years to be perfectly decomposed. Although these wastes can be utilized through recycling, reuse and energy conversion, most are consigned to landfill dumps, which can cause many undesirable environmental pollution problems.

Even though it would be almost impossible to immediately discontinue the use of petroleum-based plastics, one possible solution to the problems they cause is to introduce new materials produced from renewable feedstocks. Bioplastic, which originates from natural, renewable resources such as corn and cassava, is one such desirable alternative.

At the present time, there are only two major commercial bioplastics on the market that are biodegradable and that are truly produced from renewable sources such as sugar cane, cassava, and rice. These are polylactic acid (PLA) and polyhydroxyalkanoates (PHA) (Rudnik 2008).

The fact that bioplastic can be manufactured from cassava is key for Thailand. In 2007, Thailand's cassava production was ranked 4th in the world and it was the primary exporter to the global market (TNAIC 2007). In addition, the price of cassava in Thailand is lower than that of potato, wheat, and corn. Moreover, in 2007, a lactic acid plant was established in Thailand to produce lactic acid, which is the main raw material for the production of PLA. These factors offer Thailand a good opportunity to utilize and enhance cassava's value and use it as an industrial feed-stuff as well as a food commodity.

However, as Thailand is one of the world's leading agricultural countries and a regional petrochemical producer, a developing bioplastic industry may represent a challenge to both the country's petrochemical industry and its agricultural sector. Thus, this research aims to determine the potential of bioplastic production in Thailand. To do this it applies an analytical tool called cost-benefit analysis (CBA).

1.4 Research Objectives

The main goal of this research is to analyze the net social benefits of switching from petroleum-based plastic to bioplastic using CBA. Its specific objectives are:

1. To analyze economic estimations of the cost and benefits of PLA production.
2. To calculate the net social benefits of bioplastic production, based on the assumption that bioplastic is an alternative to existing petroleum-based plastic.

1.5 Research Questions

The study will seek to answer the following questions:

1. What gains will industry and society as a whole receive from the development of bioplastic as a new wave industry?
2. What are the costs and benefits to Thai society (investors, farmers, government, etc.) if bioplastic production is set up as an alternative to petroleum-based plastic production?

2.0 LITERATURE REVIEW

2.1 A Global Perspective of the Environmental Impact of Fossil-based Plastic Production

The literature shows that the main environmental impacts of fossil-based plastics occur during its production and usage.

The main problem associated with the production of fossil-based plastics is the emission of CO_2. It is widely known that CO_2 is a major GHG behind the global warming problem, now one of the world's leading environmental concerns. According to the IEA Petrochemical Scenarios for 2030-2050 (Gielen *et al.* 2006), petrochemicals can be categorized under the chemical and petrochemical industrial sector. Petrochemicals directly emit 18% of the total CO_2 emissions produced by this sector (excluding electricity production). However, the major CO_2 emission source in the petrochemical industry is steam cracking (Gielen *et al.* 2006), which contributes approximately 1.5 to 2.5 t CO_2/t of ethylene and 0.7 to 1.3 t CO_2/t of HV chemicals.

The main problem associated with the use of fossil-based plastics comes when they are thrown away. At present, plastic is widely used for various purposes such as packaging, manufacturing and textiles. Because plastic waste takes a few hundred years to degrade, it requires an appropriate disposal scheme to take care of it. In Thailand, approximately 2.8 million tonnes of plastic waste is produced per year. Of this waste, only 600,000 t can be recycled or transformed, so the remaining 2.2 million tonnes needs to be disposed of. Normally, plastic waste is land-filled or incinerated. This can lead to environmental impacts such as the production of acrid odors, polluted water, and the presence of plastic waste in soil or in water, which can be harmful to wildlife.

2.2 The Global Trend of Bioplastic Production and Application

Today, people around the world are facing the adverse environmental consequences of the depletion of a wide range of natural resources, especially climate change, which is caused by the use of fossil fuels and other fossil-based products. The challenge of climate change led to the development of the Kyoto Protocol (KP), an important worldwide agreement that was adopted by the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in 1997. A key goal of the KP was a reduction of at least 5% in annual GHG emissions during the first commitment period (from 2008 to 2012) for Annex I parties (which are mostly developed countries).

To help meet this goal, many successful attempts are being made to replace fossil fuels with renewable energy. In addition, a lot of research has been undertaken to find environment-friendly materials to replace plastics made from crude oil.

Plastics that are produced from petroleum are utilized in various applications. The consumption of these versatile materials has been increasing with a growth rate of 5% between 1985 and 2000 (NIA 2008). Since the global oil crisis in 1973, many attempts have been made to reduce the use of fossil-based plastics and to search for alternative materials produced from renewable sources. In the past two decades, many kinds of bioplastics have been introduced. Some are still in the research stage but some have been launched to market.

Bioplastic or biodegradable plastics are plastics that are derived from natural and renewable feedstock and which can be degraded by microorganisms after disposal. Thus, bioplastic is recognized as an environment-friendly alternative to petroleum-based plastics. The first commercial bioplastic was made by incorporating corn starch into polyethylene (PE) shopping bags to reduce the use of PE resin and to facilitate biodegradation after disposal. The next generation of bioplastics utilized naturally occurring polymers (such as vegetable oil, sugar, starch, and cellulosic fiber) as renewable feedstocks to produce plastic. For example, PLA is produced by the polymerization of lactic acid from fermentable sugar and PHAs which can be produced from vegetable oil (Shen *et al.* 2009).

The bioplastic life cycle is shown in Figure 2. The precursors for bioplastic production (which include starch, sugar and oil) are extracted from agricultural feedstocks or biomass waste. The precursors are then converted to an intermediate (a monomer), which is polymerized under optimal condition to produce bioplastic resin. End products are then manufactured from this resin using a process that is similar to that of conventional plastics.

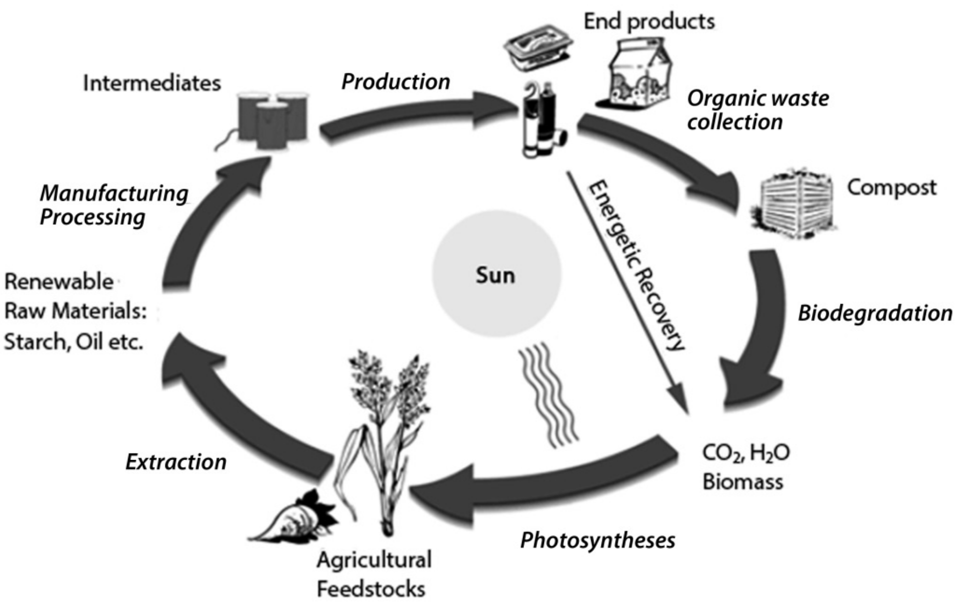

Figure 2. Life cycle of bioplastic
Source: european-bioplactics.org

After use and disposal, these bio-based products can be degraded naturally and turn to CO_2 and water within several months. The CO_2 that is emitted as they decompose is then fixed as biomass by photosynthesis. This is why bioplastic is classified as a renewable product. In comparison, when fossil-based plastics are discarded, the process of complete decomposition takes many years, while the conversion of any emitted CO_2 to its original source as petroleum takes millions of years. Consequently, the production and disposal of fossil-based plastics lead to an overall increase in the concentration of CO_2 in the atmosphere, and so exacerbate the greenhouse effect. Therefore, using bioplastics is beneficial not only because it reduces plastic waste but also because it helps mitigate global warming. In environmental terms, bioplastics therefore have advantages with respect to sustainability, reducing the use of petroleum feedstocks and decreasing GHG emissions. However, bioplastics require land for crop plantations as shown in Table 2.

Table 2. A comparison of the environmental impacts of bioplastics and petroleum-based plastics

Environmental issues	Bioplastics	Petroleum-based plastics
Renewability	Yes or partially	No
Sustainability	Yes	No
Degradability environment	Biodegradable and/compostable	Some degradable by polymer oxidation
GHG emissions	Usually low	Relatively high
Fossil fuel usage	Usually low	Relatively high
Arable land use	Currently low	None

Source: HGCA 2010

An overview of several bioplastics is presented in Table 3. All the plastics shown in the table (except Polytrimethylene terephthalate (PTT)) are derived from renewable materials. Some of the plastics (such as starch plastic, cellulose polymer and PLA) have been commercialized. According to European Bioplastics (2008), the global production capacity of bioplastic is nearly 300,000 t/ year. This represents only a 1% market share of the total global plastics business. By 2011, the production capacity had quadrupled to over a million tons. The majority of bioplastic producers are in EU countries. European Bioplastics estimates that the annual growth in the European bioplastic industry is significantly higher than 20%.

Table 3. Overview of the current most important groups and types of bioplastics

Bio-based plastics	Type of polymer	Types/structure/production method
Starch plastics	Polysaccharides	Partially fermented starch; Thermoplastic starch (TPS); Chemically modified starch; Starch blends; Starch composites
Cellulose polymers	Polysaccharides	Organic cellulose esters; Regenerated cellulose
Polylactide (PLA)	Polyester	Bio-based monomer (lactide) by fermentation followed by polymerisation
Polytrimethylene terephthalate (PTT)	Polyester	Bio-based 1,3-propanediol (1,3-PDO) by fermentation plus petrochemical terephthalic acid (or DMT)
Polymides (PA)		
a. PA 11	Polymide	Bio-based monomer 11-aminoundecanoic acid from castor oil
b. PA610		Monomer sebacic acid from castor oil
c. PA6		Bio-based monomer caprolactam by fermentation of sugar
d. PA66		Bio-based adipic acid bby fermentation
e. PA69		Bio-based monomer obtained from oleic acid via azelaic (di)acid
Polyhydroxyalkanoates (PHAs)	Polyester	Direct production of PHA by fermentation
Polyethylene (PE)	Polyolefin	Bio-based monomer ethylene obtained from ethanol; ethanol is produced by fermentation of sugar
Polyvinylchloride (PVC)	Polyvinyls	Monomer vinyl chloride can be obtained from bio-based ethylene (from ethanol)

Table 3 continued

Bio-based plastics	Type of polymer	Types/Structure/Production Method
Other thermoplastics		
a. Other polyesters (PBT, PBS, PBSL, PBSA, PBST, PBAT, PET, PEIT PVAc, Polyacrylates, PTN, PTI, thermoplastic elastomers)	Polyester	Various carboxylic acids, various alcohols
b. Other ethylene-based compounds (e.g polystyrene and EPDM rubber)	Various	Ethylene by dehydration of bio-ethanol reacted with other compounds

Source: Shen *et al.* 2009

A forecast for worldwide bioplastic production capacity in 2020, and an overview of key manufacturers, is shown in Table 4. It is projected that by 2020 the production of starch plastic will contribute 38% of the total production capacity, followed by PLA at 24%. The major players for starch plastic production are Cereplast, Biotec and Novamont, which have a total capacity of 950 kt. The important manufacturers for PLA are NatureWorks and Purac and partners which, between them, have a total capacity of 750 kt.

Table 4. Worldwide share of bioplastics by type and major players in 2020

Type of bio-based plastics	Share of global bio-based plastics capacity	Production capacity of major global players
Starch plastics	38%	Novamont: 200 kt [3]; Biotec; 300 kt [3]; Rodenburg: 40 kt [b]; Plantic: 15 kt [c]; BIOP: 280 kt [a]; Cereplast: 450 kt [a]; Livan: 110 kt [c]
PLA	24%	Nature Works: 450 kt [b]; Purac and partners: 300 kt [b]; Pyramid: 60 kt [c]; TeijinF: 10 kt [c]; HiSun: 5 kt [c]
Bio-based Ethylene	18%	Braskem: 200 kt (PE) [c]; Dow-Crytalsev: 350 kt (PE) [c]; Solvay: 60 kt (Ethylene) [c]
PHA	13%	TElles: 50 kt [c]; Tianan: 50 kt [c]; Kaneka: 50 kt [a]; Meredian: 272 kt [c]; DSM/GreenBio: 10 kt [c]
Bio-based Monomers	6%	Dow: 100 kt (ECH) [c]; Solvay: 110 kt (ECH) [c]
Other	2%	Innovia: 20 kt (cellulose films) [a]; DuPont: 10 kt (PTTC) [c]; Arkema: several thousand tonnes of PA 11 [b]
Total	**100%**	

[a] Data collected from the questionnaire/survey
[b] Data collected from personal communications
[c] Data collected from publicly available company announcements
[d] Including PLA volumes at Purac partners
Source: Shen *et al.* 2009

The projections of bioplastic production capacity from a number of different studies are illustrated in Figure 3. The PROBIP 2009 (business-as-usual or BAU scenario) projects that the bioplastic market will have a production capacity of 2.94 million tonnes in 2020. However, it also projects production capacities for LOW and HIGH scenarios of approximately 1.4 and 4.4 million tonnes, respectively. The projections outlined by Crank *et al.* (2005) present potential increases of production capacity with and without supporting policies and measures (PM). These show that the expansion of bioplastic production will rely on policies and measures put in place by governments and driven by international environmental concerns.

The PROBIP senario studied by Shen *et al.* (2009) indicates that bioplastics have the potential to replace 236,500 kt of fossil-based plastics in 2020. As shown in Figure 4, the production capacity of bioplastic is set to increase from 360 kt in 2007 to 3,450 kt in 2020. However, this projection is based only on what is technically feasible. The real difficulty of introducing new bioplastics to the market is whether they can compete on price with existing petrochemical plastics that have been in use for up to five decades.

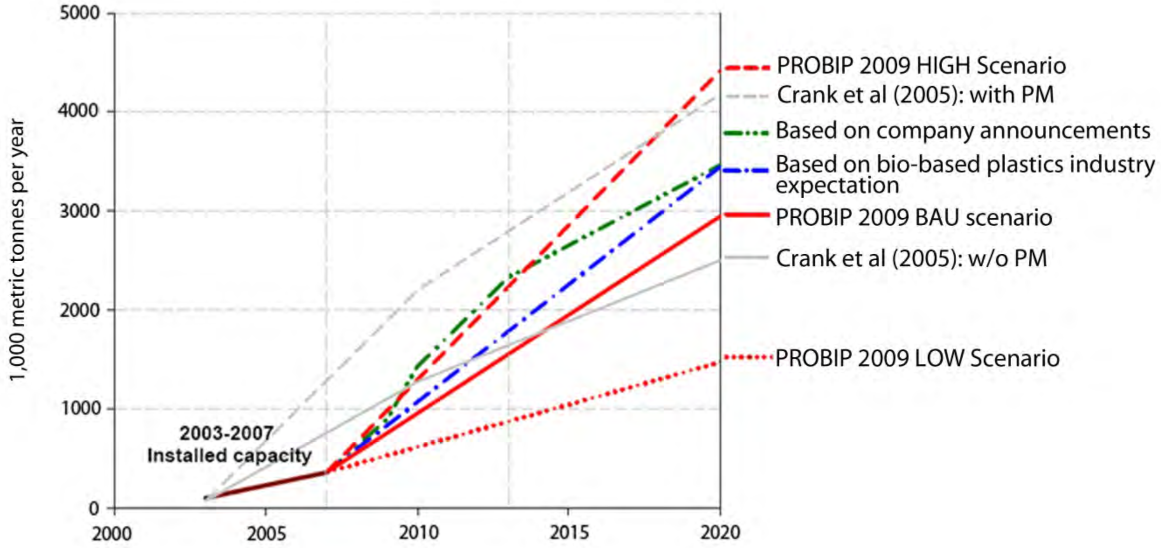

Figure 3. Projection of the worldwide production capacity of bioplastics until 2020
Source: Shen *et al.* 2009

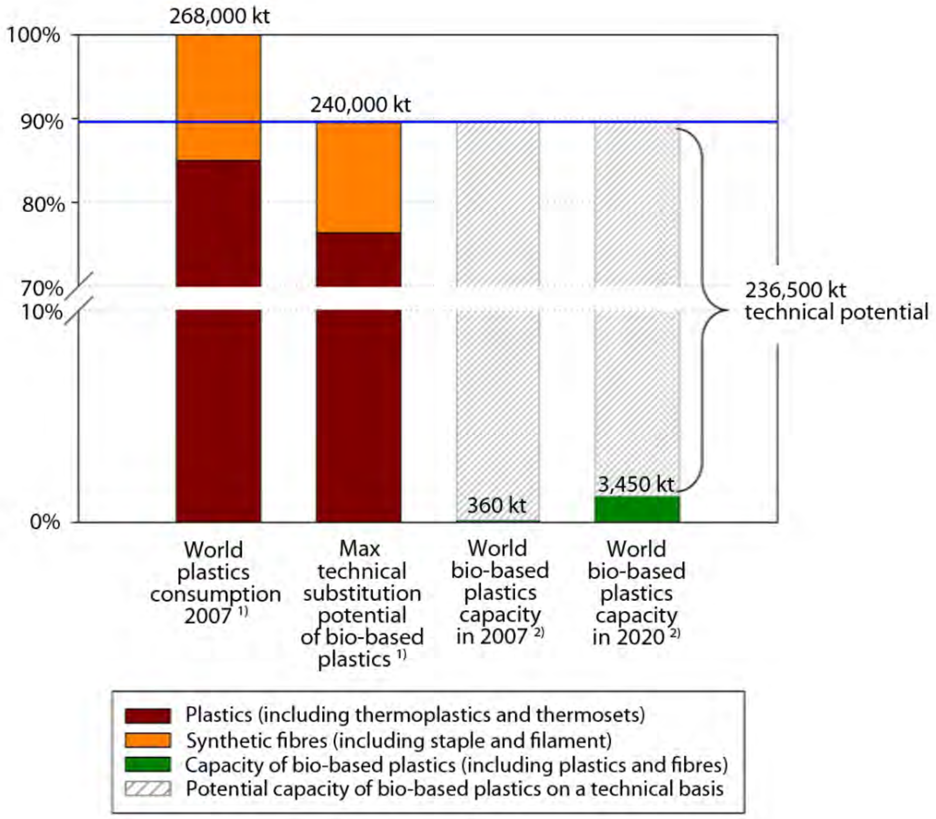

Figure 4. Comparing the world-wide projections with the market potential, based on the maximum technical substitution potentials
Source: Shen *et al.* 2009

Currently, the price of bioplastic is approximately twice that of conventional plastic produced from petroleum. However, increasing oil prices and environmental concerns are important factors that will reduce this price disparity and drive the demand of bioplastics. Bulk production will also play a key role in reducing production costs and increasing the demand for bioplastic. However, if bioplastic remains uncompetitive with conventional plastics, then the development of bioplastic for high-end products (where price is not such a critical issue) should be prioritized.

2.3 The Current Situation of Cassava Starch Production in Thailand

Cassava is one of the most important economic crops in Thailand. The country's annual cassava production capacity is approximately 17 t/ha (Sriroth *et al.* 2006). Thailand's cassava plantation areas, productivity and costs of cassava production during the years from 2007 to 2009 are presented in Table 5. Information on domestic cassava consumption and cassava exports are shown in Table 6.

Table 5. Plantation area, productivity and cost of cassava production in Thailand, 2007-2009

List	2007	2008	2009
Plantation area (ha)	1,174,209	1,183,535	1,326,743
Production (t)	26,915,541	25,155,797	30,088,024
Cost (THB/t)	824	1,079	1,229
Sale price (THB/t)	1,180	1,930	1,190

Source: OAE 2010

Table 6. Consumption and export of cassava products in Thailand, 2007-2009

List	Year 2007	Year 2008	Year 2009
Domestic consumption (million tonnes fresh root)	7.73	9.03	9.01
Export chips (tonnes)	2,680,451	1,202,463	4,000,000
value (million THB)	11,136	6,540	18,400
Export pellets (tonnes)	1,650,731	1,564,341	260,000
value (million THB)	7,195	8,681	1,200
Export tapioca (tonnes)	2,206,991	1,987,278	24,000,000
value (million THB)	26,912	29,795	28,200

Source: OAE 2010

Fresh cassava roots can be processed into more valuable products such as cassava chips, starch and pellets as illustrated in Figure 5. Most of these products (67%) are exported worldwide (Thailand's market share in these products was 82% in 2009). The rest of these products are used for domestic consumption: 19% as food for human consumption (starch, sugar and lactic acid), 8% as animal food, and 6% as the raw materials for bioethanol production (OAE 2010).

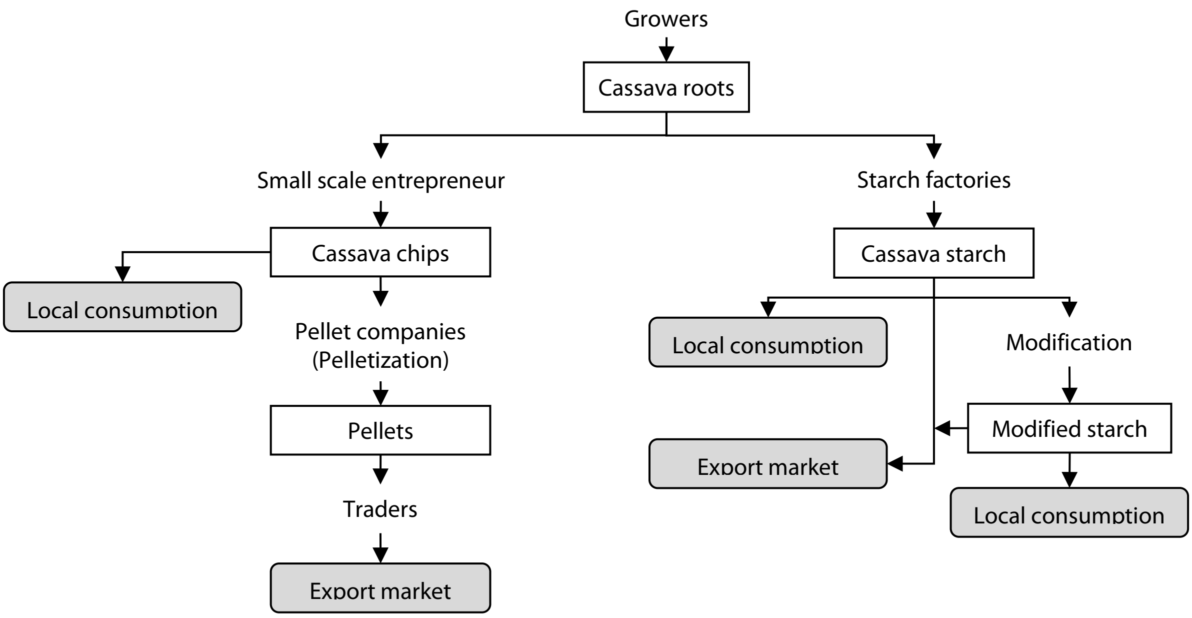

Figure 5. Market structure of cassava in Thailand
Source: Sriroth *et al.* 2006

Thailand is the world's largest exporter of starch produced from cassava (which is sometimes called tapioca). Only 20% by weight of fresh root harvested is delivered to starch production plants. According to a recent survey, there are 73 starch production plants in Thailand, which have a total starch production capactiy of 20,000 t/day (TTSA 2010). Each year, 1.2 million tonnes of this starch is used domestically and 2.3 million tonnes are exported.

The traditional process of starch production from cassava is usually practiced in small- and medium-scale plants. The common process involves seven steps: root washing, grinding, fiber separation, starch extraction, dewatering, drying, and packing (Chavalparit and Ongwandee 2009).

A mass balance of the raw materials and resources used in cassava starch production is shown in Figure 6. One tonne of starch is derived from 4.21 t of cassava roots. It is clear from this mass balance that cassava starch production requires large amounts of water, which is then discharged as wastewater (19.1 m^3/t of starch). The wastewater generated from starch production has a high BOD loading (112 kg/t of starch), which is commonly treated using areated lagoon technology. However, some solid wastes from the production process, like fibrous residues and peel, can be sold as cassava meal for animal food and utilized for biogas and bioethanol production.

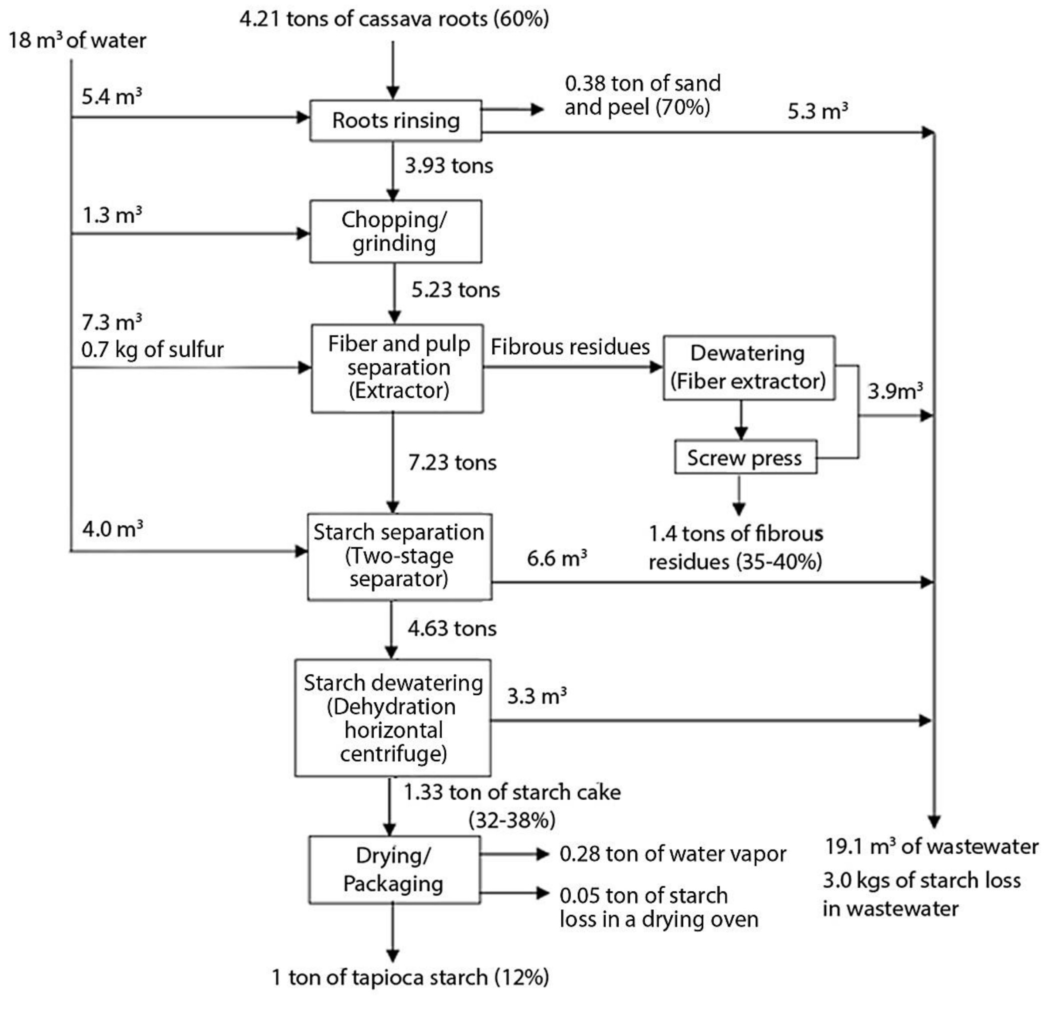

Figure 6. Mass balance of raw materials and resource used in cassava starch production
Source: Chavalparit and Ongwandee 2009

The major energy sources for the cassava starch production process are electricity and fuel oil. Currently, some large-scale starch plants in Thailand utilize biomass waste as fuel in an on-site power plant and/or use biogas as an energy source. This biogas can be produced on site, if the plant uses an anaerobic digester (e.g., an Upflow Anaerobic Sludge Bed or UASB) for wastewater treatment. Biogas produced from the digester can be used to generate electricity.

When starch plants generate their own power from renewable resources, they can sell the carbon emissions they offset as carbon credits under the Clean Development Mechanism (CDM). These carbon offsets are based on the reductions in fossil fuel use and methane emissions that the plants are responsible for. The additional revenue raised from selling carbon offsets is an incentive that can encourage companies to improve their production efficiency in terms of natural resource usage and environmental concerns.

According to data from the website of the Thailand Greenhouse Gas Management Organization (TGO 2010), 118 CDM projects have received a Letter of Approval (LoA) from the TGO; these comprise biogas projects (69.50%), biomass projects (18.95%) and others CDM projects (11.55%). The overall potential GHG reduction from the projects that have received LoA is 7,379,979 $tCO_{2\ (eq)}$/year. Examples of CDM projects related to starch production plants in Thailand are detailed in Table 7.

Table 7. Example CDM projects developed from utilizing biogas from cassava starch production plants

CDM projects	Project life (years)	GHG reduction ($tCO_{2\ (eq)}$/year)	Electricity produced (MW)
1. Wastewater treament with biogas technology in a tapioca processing plant at P.V.D International Company Limited.	20	50,663*	2.8
2. Wastewater treatment with biogas technology in a tapioca processing plant at Roi Et Flour Company Limited.	20	40,276	1.4
3. Bangna Starch wastewater treatment and biogas utilization project	30	41,701	2.6
4. Tapioca starch wastewater biogas extraction and utilization project at Eiamburapa Company Limited.	30	56,004	2.2

* The reduction amount when registered to the CDM Executive Board
Source: TGO 2010

The production cost of cassava starch depends on production efficiency. Generally, large-scale plants have lower costs than small ones. Chavalparit and Ongwandee (2009) studied the cost structure of cassava starch production at eight plants (one large, four medium and three small). The cost of cassava roots made up the majority of the production costs of these plants (80% of the total). The cost of the electricity used in starch processing made up 9% of total costs, while the cost of fuel made up 5%. The other costs were water supply (1%) and labor (2%).

This study proposed several options to reduce production costs. One interesting option was the recovery of biogas to replace the fuel oil in the burner (the machinery used to ignite fuel). This would entail an investment cost of THB 24 to 55 million and will provide a benefit of THB 13 to 24 million/year. Additionally, the carbon offset earned from such a project could be sold under the CDM program or even in the voluntary emission reductions (VERs) market (which is one type of carbon credit market). The GHG emission reductions are exchanged in the VERs market through a voluntary certification process.

3.0 RESEARCH METHODOLOGY

3.1 The Tools of Analysis

This study used CBA to evaluate bioplastic production. This was done to help inform public sector decision making about pursuing bioplastics as a new wave industry. The CBA was conducted to evaluate the costs and benefits of bioplastic production as a replacement for the production of fossil-based plastics. The study followed nine key steps:

Step 1: Specify the set of alternative projects. The portfolio of the projects assessed in this study consists of two scenarios:

- *Scenario 1*: This is the status quo scenario in which no bioplastic production is introduced. The baseline is therefore only the production of a comparable petroleum-based plastic, in this case HDPE.
- *Scenario 2*: The new scenario in which PLA bioplastics production takes place, with a production capacity of 100,000 t.

Thus, this study is based on the assumption that the production of conventional plastics is not totally replaced by the production of bioplastic.

Step 2: Decide to whom benefits and costs relate to. The referent group refers to the group(s) of individuals whose welfare will be referred to when assessing the costs and benefits of the project. Within this study, the people of Thailand are the referrent group. This groups contains a number of sub-groups within it. These are: 1) the fossil-based plastic and bioplastic industries, 2) cassava farmers, and 3) the govenment.

The referent group (and sub-groups) was selected based on policy decisions about who will receive the benefits and welfare improvements that will flow from the implementation of the National Roadmap for the development of bioplastics production. Scenario 2 shows which groups will gain and who will lose from the introduction of bioplastics. For example, farmers and society as a whole may gain social benefits from substituting HDPE with PLA. However, the fossil-based plastic industry may lose some of its market share.

Step 3: Catalogue the impacts and select measurement indicators. The potential positive and negative impacts used in this study are itemized in Table 8. In summary, the potential costs of PLA production include raw material costs (cassava roots and chemicals), capital costs, labor costs, operation costs and waste treatment costs. While, direct benefits will be derived from by-products such as fodder, organic acids, ethanol and gypsum.

Table 8. Potential costs and benefits of PLA production

Production process	Costs	Benefits	Data sources
1. Starch production	Investment costs Operation costs Costs of waste water treatment	Animal feed products	Research journals, plant owner interview
2. Lactic acid production	Investment costs Operation costs Costs of waste water treatment	By-products such as ethanol and gypsum	NatureWorks, NIA, research journals
3. PLA polymerization	Investment costs Operation costs	Carbon offset Reduction in hazardous waste treatment costs	NatureWorks, NIA, research journals

Moreover, PLA production will provide social benefits in terms of carbon offsets; these can be evaluated by assessing the difference in GHG emissions between PLA and conventional plastic production. PLA produced from cassava is a biomass-based material. Net carbon emissions from biomass use are considered to be zero. In comparison, the production of conventional plastics from petroleum is responsible for significant carbon emissions, and this can be taken into account when assessing the benefits of PLA production.

Additional social benefits will be derived from PLA production due to a decrease in the environmental pollution that is emitted from the conventional plastic production process. This pollution includes toxic and carcinogenic residuals, volatile organic compounds, acid gases, and wastewater. The value of this indirect benefit can be evaluated from the cost of hazardous waste treatment.

Step 4: Predict the impact quantitatively over the life of the project. Bioplastic production will have an impact over an extended period of time. This study assumes a time horizon of 25 years due to the timeframe of the current roadmap for the development of the bioplastic industry.

The study aimed to predict the magnitude of all impacts in terms of measurable units over the life of a particular project. If there are any impacts that cannot be quantified or measured in physical units (for example, social and cultural impacts), relevant descriptive information was provided. Sometimes, the required information may not be available for assessment purposes. In such cases, analysts made certain assumptions to estimate the value of anticipated impacts.

Step 5: Monetize all impacts. The monetization of outputs and impacts does not imply that money is all that matters. It is merely a convenient way of translating the physical measurement of any impacts into comparable common units (Hanley *et al.* 2000).

Given that many environmental goods and services are not traded in the market, there are often no prices to use as a reference. Shadow prices must therefore be used to reflect the true economic values of any cost and benefit. In this study, the benefit transfer method is used to estimate a shadow price for unavailable cost and benefit values. Environmental values are estimated from existing studies or secondary data. Fixed value transfer and the use of expert opinions are adopted to derive the monetary values used in calculations. In addition, shadow exchange rate (SER) for tradeables and non-tradeables is adopted as a proxy for the economic price of foreign currency.

Step 6: Discount benefits and costs to obtain their present values. Net present value (NPV) is computed by assigning monetary values to benefits and costs, discounting future benefits and costs using an appropriate discount rate, and subtracting the sum total of discounted costs from the sum total of discounted benefits. The discounting reflects the time value of money. Discounting benefits and costs transforms gains and losses occurring during different time periods into a common unit of measurement.

In this study, the NPV is calculated for PLA production starting from cassava starch and for three other options: 1) a change in benefits due to expected PLA price developments, 2) a change in costs due to expected technological developments, and 3) a combination of options 1 and 2.

A 25-year project life time is assumed. All future benefits and costs of bioplastic production (including non-monetized benefits and costs) are discounted over this time period. For bioplastic production projects, costs are concentrated at the beginning of the project and benefits follow later. This means that raising the discount rate will tend to reduce the NPV of any project. A real discount rate that reflects expected inflation is used to discount nominal benefits and costs. In November 2009, the Bank of Thailand issued a 30-year interest rate on government bond yields of 4.29%, which gives a real discount rate of 1.29%.

The sum of discounted benefits and costs of the different projects is then compared. This comparison constitutes the main criteria for choosing amongst projects. In principle, all projects with NPVs greater than 0 are considered to have passed the NPV test since this result is deemed to represent an improvement in social welfare.

A number of other criteria such as the Benefit-Cost (B/C) ratio and the Internal Rate of Return (IRR) are useful as supporting information, however they are not decisive factors in determining whether or not a project should be adopted. The B/C ratio indicates the cost-effectiveness of investment, while the IRR can support decision-making by comparing the returns of one project against another relative to the opportunity cost of funds (Hanley *et al.* 2000).

Step 7: Compute the net present value of each alternative. The NPV of a project is equivalent to the present value of its total costs minus the present value of its total benefits. With the project time frame of this study being 25 years, the NPV is calculated using the following equations:

$$NPV = V_0 + \frac{V_1}{(1+i)} + \frac{V_2}{(1+i)^2} + \ldots + \frac{V_t}{(1+i)^t}$$

$$\text{NPV} = \sum_{t=0}^{n} \frac{V_t}{(1+i)^t}$$

where: V_t = value at time t
I = discount rate
t = year
n = 0,1,2,….,25

Step 8: Perform a sensitivity analysis. The purpose of a sensitivity analysis stems from potential uncertainties over various assumptions that relate to a project's parameters and their future relative values (Folmer and Gabel 2000). Sensitivity analysis is therefore an essential stage in a CBA and determines the sensitivity of the NPV given changes in key parameters.

The parameters that deserve the most attention will depend on the dominant benefit and cost elements. They will also depend on the areas of greatest uncertainty within the program being analyzed. In the year 2005, the rate of Thailand government bond increased to 6.72%, which is higher than the present rate (4.29%). In this study, sensitivity analysis is undertaken for estimates of different real discount rates of 1.29%, 3.29% and 5.29% with an inflation rate of 3% during the 25-year period.

Step 9: Make a recommendation. After having completed the successive steps described above, the interpretation of the results of the CBA is finally made. This is done with recognition of the CBA tool's strengths and limitations. Limitations can arise from the fact that a number of parameters may be unpredictable, while others maybe unknown (Hanley *et al.* 2000).

Even though there are already some existing policies in Thailand that are relevant to bioplastic production, the outcome of this study will still be beneficial to Thai policymakers such as the National Innovation Agency (NIA) and Office of Natural Resources and Environmental Policy and Planning (ONEP) and should help them initiate new environmental laws and amend existing legislation.

3.2 Data Collection

The direct and indirect use values will be defined in terms of costs and benefits for both PLA and HDPE. These data were gathered from primary and secondary data sources. In some cases, primary data was collected from relevent stakeholders by a variety of approaches including face-to-face interviews with experts.

The cost of know-how and technology for PLA resin production and the capital cost of a pilot plant was provided by NIA and the well-known firm NatureWorks. This information included research documents.

The market prices of Lactic acid monomer, PLA resin and conventional plastic resin were provided by the international alliance of bioplastic associations and petrochemical companies.

The cost and benefits of the environmental aspects of PLA production were assessed by analysing the reduction in GHG emissions that occur when fossil-based plastics are replaced by bioplastics. This was done in terms of a carbon-credit trade.

4.0 POLYETHYLENE PRODUCTION IN THAILAND

Polyethylene is the most important and widely used commodity plastic in the world. Thailand's total polyethylene production capacity (as of 2007) amounted to 2.6 million tonnes (PTIT 2008).

There are three types of polyethylene, namely: low density polyethylene (LDPE), linear low density polyethylene (LLDPE), and high density polyethylene (HDPE). Among these, HDPE is the most widely-used (approximately 1.5 million tonnes). The applications of HDPE include film packaging, rigid containers, monofilament, wire and cable. Considering its widespread consumption, HDPE was selected to be the fossil-based plastic to be compared with PLA.

4.1 HDPE Production Process

The current commercial HDPE production technologies are the Ziegler slurry, slurry loop, gas phase, and solution processes. Table 9 presents a summary of available licensees of each technology (Fekete 2009).

Table 9. HDPE licensees by process type

Ziegler Slurry	Gas Phase	Slurry Loop
LyondellBasell (Equistar-Maruzon)	LyondellBasell, LUPOTECH G	Borealis, BORSTAR
LyondellBasell, HOSTALEN	Univation, UNIPOL PRODIGY	Chevron Phillips
Mitsui, Mitsui CX		INEOS, INNOVENE S

There are three HDPE producers in Thailand (IRPC 2009), namely: Integrated Refinery & Petrochemical Complex (IRPC), SCG Chemicals, and PTT Polyethylene Company Limited (PTTPE). Each manufacturer's production capacity is shown in Figure 7. The Mitsui CX production process is considered in this research as both PTTPE and SCG use this licensed technology. The process flow diagram of the CX process (Mitsui Chemicals n.d.) is illustrated in Figure 8.

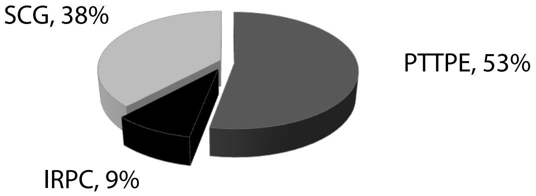

Figure 7. HDPE production by manufactures

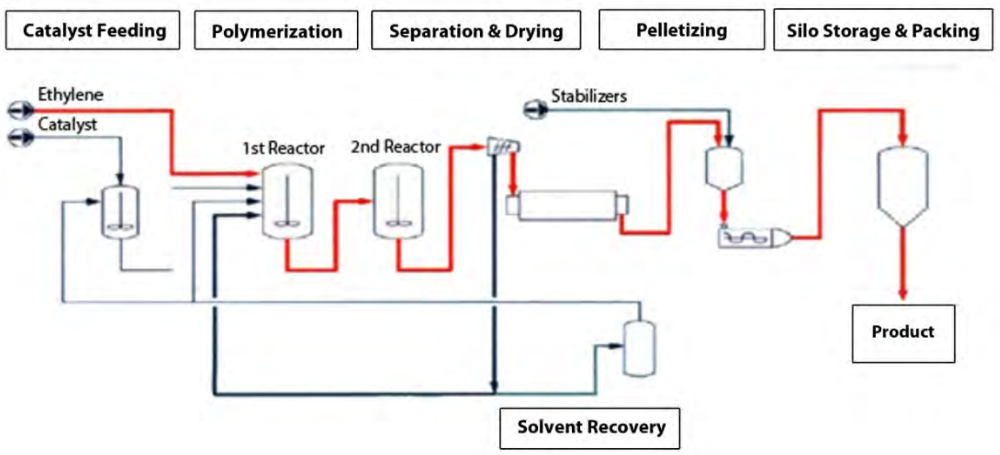

Figure 8. Process flow diagram of the HDPE Mitsui CX technology

The process uses ethylene as a feedstock, this is polymerized with a high-activity catalyst in two reactors before it is fed into a separation and feeding system. The drying polymer is then pelletized and stored in a silo for packing.

The two-reactor system enables the manufacture of bi-modal HDPE. Moreover, the molecular weight distribution of the finished product can be independently tailored by simply adjusting reactor-operating parameters.

4.2 HDPE Market Trend

The majority of HDPE is produced as film for various products such as food packages, wrapping, refuse sacks, carrier bags and industrial liners. The growth of HDPE in the global market is around 5% per year.

In Thailand, the price of commodities such as polyethylene and polypropylene is unpredictable. For example, the prices of film-grade HDPE in Thailand (which is used as the reference in this research) fluctuated considerably during 2008-2010 (TPIA 2010). Crude oil is one of the primary raw materials for petrochemical products and its price is believed to have a significant impact on the price of plastic. To illustrate this, a comparison between the price of HDPE and crude oil is depicted in Figure 9 (EIA 2010). It demonstrates the correlation between HDPE and crude oil prices from 2008 to 2010.

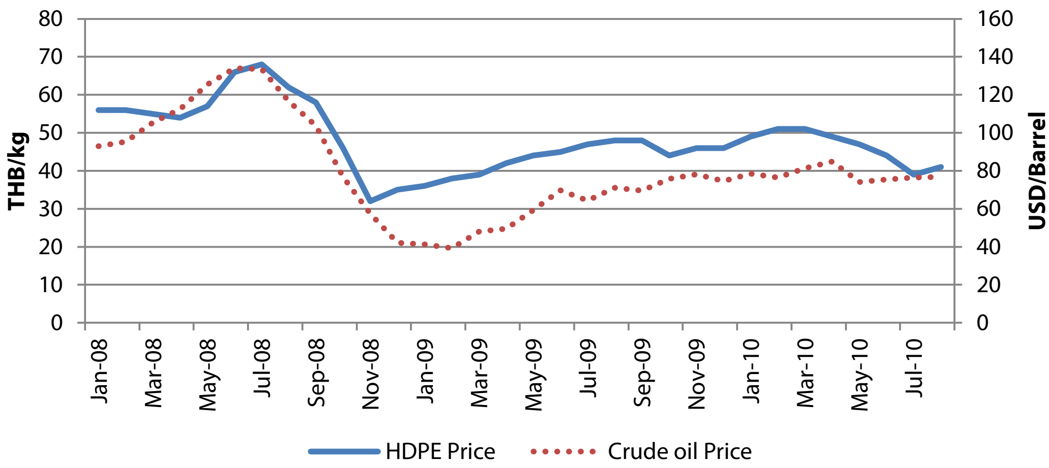

Figure 9. HDPE price (Film grade) in Thailand vs. Crude oil price (Nymex) during 2008-2010

5.0 POLYLACTIC ACID PRODUCTION

Polylactic acid (PLA) is an aliphatic polyester. It is produced via the polymerization of lactic acids, which are renewable fermentation products. It is made from 100% renewable resources such as corn, sugar beet, wheat, and other starch-rich products.

In 2002, the first PLA production plant was launched by Cargill Dow, U.S.A. This company is now trading as NatureWorks LLC. In this first production plant, corn starch was used as a raw material to produce lactic acid (the PLA precursor). In 2007, Purac Netherlands, used cane sugar to produce lactic acid and lactide as precursors for various markets, including PLA production. The advantages of PLA are biodegradability, recyclability, compostability, non-toxicity, strength and durability, breathability, and oil and grease resistance. Today, PLA products are well-known and are used in a variety of ways, for example as biomedical materials, drug delivery devices, compostable packaging, fiber and non-woven textiles (Rafael *et al.* 2010).

5.1 PLA Production

The PLA production process involves the conversion of biomass to starch or sugars (glucose and dextrose), the production of lactic acid or lactide (a monomer used for production of PLA) from the fermentation of these sugars, the purification of lactic acid and the polymerization of lactic acid (Vink *et al.* 2003). The types of biomass that can be used as a raw material in this process include corn, sugar cane, wheat, cassava, beet or any lingo-cellulose material (Vink *et al.* 2003; Dornburg *et al.* 2006).

The process of lactic acid production involves treating soluble calcium lactate with sulfuric acid to precipitate gypsum as a by-product (approximately 1 t of gypsum is produced per tonne of lactic acid). The purification process is a combination of esterification, distillation, the hydrolysis of ester, and the recovery of alcohol by evaporation (Shen *et al.* 2009).

There are two main ways to convert lactic acid to PLA. The first route, employed by NatureWork and Purac, starts with the condensation of lactic acid to produce lactide. This is followed by the ring-opening polymerization of lactide to obtain PLA. The second route involves the direct polymerization of lactic acid. This approach has been used by Mitsui Toatsu, but it is not currently being employed (Shen *et al.* 2009). The polymerized product is PLA resin, which is ready to be processed into products.

After use and disposal, PLA products can be naturally degraded by microorganisms (they decompose to form CO_2 and water). The PLA production diagram is presented in Figure 10.

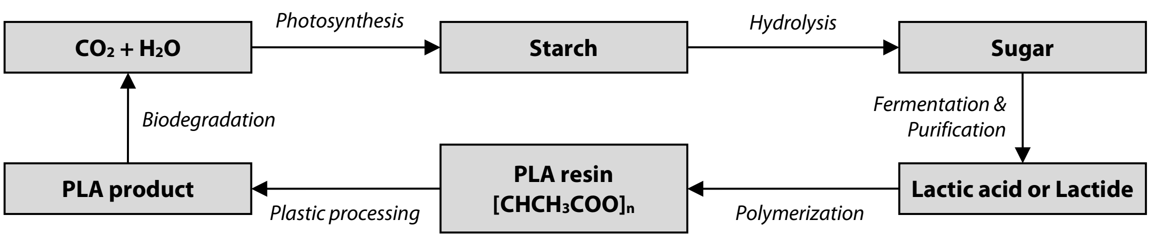

Figure 10. PLA production from biomass

The conversion of biomass to PLA depends on the starch content of the raw material or the amount of sugar produced. The yield of corn to PLA is 1.74 kg PLA/kg of corn (Vink *et al.* 2003). The yield of sugar to PLA is 0.95-1.09 kg PLA/kg of sugar (Johansson 2005). The yield of cassava starch converted to glucose was reported by Sriroth *et al.* (1998). Cassava planted in Thailand generally has a 25% by weight starch content; this can be converted to glucose syrup with a yield of 95%.

NatureWorks LLC was the first large-scale PLA producer in the world. Its PLA production plants are located in Blair, Nebraska, U.S.A. and have a production capacity of 140,000 t/year. The process employed by NatureWorks uses corn with a 15% moisture content as raw material. The consumption of corn for PLA production takes up approximately 0.15% of the total amount of corn produced in the U.S.A. (WBCSD 2010). NatureWorks' PLA products are marketed under the brand of NatureWorks® and Ingeo™. It has been reported that NatureWorks has the potential to use low-cost starch crops such as cassava, maize or rice as feedstocks for its PLA production. If competition becomes stiff for agricultural crops in the future, NatureWorks plans to use cheap biomass waste such as ligno-cellulosic fiber from corn stover (corn fibre) instead (Vink *et al.* 2003).

Purac Netherlands is the largest producer of lactic acid and its derivatives in the world. In 2007, Purac started up a lactic acid production plant in Rayong province, Thailand. The process employed at this plant uses sugar from sugar cane to produce lactic acid and lactate which are then supplied to the food, chemical, pharmaceutical and cosmetic industries. In 2010, Purac started the construction of a new lactide plant at its existing site, which started up in 2011 with an annual production capacity of 75,000 t. Recently, Sulzer Chemtech and Purac have jointly developed a new, cost-effective polymerization process to produce high-quality PLA. Purac supplies lactide precursors and supports Sulzer polymerization technology (Purac 2010). The product is a foamed PLA. It is marketed under the band of BioForm® and can be competitive with conventional polystyrene foam. The company has set itself a target capacity of 5,000 t/ year (globally), to be operational by the end of 2009.

The environmental benefits of PLA are renewability, sustainability and biodegradability. A comparison of the GHG emissions from the production of petroleum-based plastics and PLA has been studied by many researchers (as shown in Table 10). However, the values obtained by these studies differ due to the differing scope of each study. Some of the studies were Life Cycle Assessments. These involved the study of environmental impacts starting from the extraction of raw materials, through manufacturing and use and onto disposal (*Cradle-to-Grave* assessments). In contrast, some of the studies only focused on the production process (*Gate-to-Gate* assessments).

Table 10. GHG emission of plastics in unit of CO_2 equivalent

Plastics in pellet form	GHG emission (kg $CO_{2\,(eq)}$/kg plastic)	Scope of study[a]	References
Starch polymer	1.1 - 3.6	Cradle-to-Grave	Martin 2001
HDPE	5.07	Gate-to-Gate	Dornburg *et al.* 2006
HDPE	2.14	Cradle-to-Gate	TGO 2009
LDPE	4.80	Cradle-to-Grave	Martin 2001
PP	1.97	Cradle-to-Gate	TGO 2009
PET	5.02	Gate-to-Gate	Dornburg *et al.* 2006
PET	7.54	Cradle-to-Gate	TGO 2009
PLA (from sugar)	0.50	Cradle-to-Gate[b]	Groot 2010
PLA (from wheat)	0.74	Gate-to-Gate[c]	Dornburg *et al.* 2006
PLA (from corn)	1.80	Cradle-to-Gate	Vink *et al.* 2003
PLA (from corn)	4.20	Cradle-to-Grave	Johansson 2005

[a] Life cycle assessments can be divided into three main categories: cradle-to-gate (factory gate), gate-to-gate, gate-to-grave.
[b] Combined with co-generation of electricity (using biomass waste) in the sugar refining.
[c] From energy consumption in the PLA production process only.

The findings on GHG emissions from PLA also varied between these studies. PLA resins produced from sugar, wheat and corn have been found to emit between 0.5 and 4.2 kg $CO_{2\,(eq)}$/kg of PLA. This variability was due to differences in aspects such as calculation boundaries, the types of crops used as raw materials, waste treatment technologies, fuel use and energy efficiency.

Despite these differences, it is obvious from these studies that petroleum-based plastics such as HDPE, LDPE, PET, PP or even starch polymer (plastic blended with starch) are responsible for more GHG emissions than PLA.

5.2 PLA Market

The market share of major bioplastics is illustrated in Figure 11. The largest contribution belongs to starch polymers, which have a 40% share of the market; these are followed by extruded starch (20%). PLA and cellulose acetate have 15% of the total market share (HGCA 2010).

The most common uses of PLA are compostable packaging and textiles. The prices of bioplastics and petroleum-based plastics are presented in Table 11. In 2007, the price of PLA resins was at least twice as high as that of conventional plastics. Shen *et al.* (2009) reported that in 2007 the price of PLA resin supplied by NatureWorks LLC was USD 2.4/kg. The production cost of PLA estimated by Inventa Fischer was USD 1.97-2.42/kg.

According to Nature Works LLC, the major cost of PLA production comes from lactic acid production, which contributes between 40-50% of the total cost. Similarly, Purac estimated that 50% of any initial investment in PLA production is required for lactic acid production (30% is required for lactide production and 20% for polymerization).

Certainly, cost is the biggest challenge when it comes to increasing PLA's market share. Even though crude oil prices in 2009 were lower than usual, the cost of PLA was still higher than that of conventional plastics. However, it is clear that economies of scale could reduce the price differential. Additionally, relevant environmental policies and regulations could facilitate investment in the bioplastic industry and strengthen the market for bioplastics.

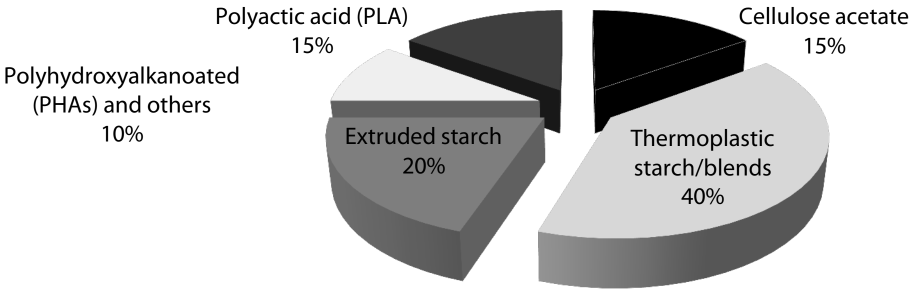

Figure 11. Bioplastics market shares
Source: HGCA 2010

Table 11. Price of plastics, 2007-2009

Plastic resins	Price (USD/kg)			References
	2007	2008	2009	
HDPE	1.3	1.5	1.4	OIE 2010
LDPE	1.3	1.7	1.4	OIE 2010
PET	1.2	1.3	1.3	OIE 2010
PP	1.3	1.4	1.2	OIE 2010
PVC	0.8	1.0	0.8	OIE 2010
PLA	1.97-2.42	N.E.	N.E.	Shen *et al.* 2009

Note: N.E. - not estimated

6.0 COST-BENEFIT ANALYSIS OF POLYLACTIC ACID PRODUCTION

6.1 HDPE Production Process and Input Data

In Thailand, HDPE is produced from naphtha- and ethane-based feedstocks. This research evaluated the production costs of naphtha-based production using the Ziegler Slurry process licensed by Mitsui Chemical (Mitsui CX process). This process accounts for 91% of all HDPE production in Thailand. The study assessed the production of 100,000 t of HDPE (to allow a direct comparison with the production of 100,000 t of PLA).

According to IPPC (2007), the average level of ethylene consumption in HDPE production is 1.027 t/t of HDPE. The ethylene yield from naphtha (using the steam cracking process) is approximately 28.4 t/t of naphtha (IPPC 2003). Information from the European Plastic Industry shows that, in an oil refinery, 1 t of naphtha is produced from 1.1 toe (tonnes of oil equivalent). Figure 12 shows the mass and energy balance of HDPE production.

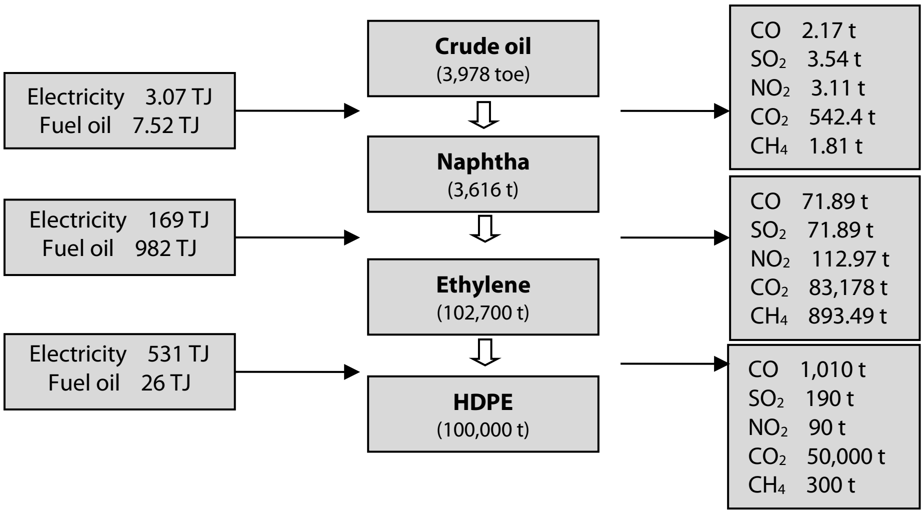

Figure 12. Mass and energy balance of HDPE production

Table 12. Input data of HDPE production from naphtha

	Quantity	References
Raw material		
Crude oil	3,978 toe	Eco-profiles of the European Plastic Industry
Products		
HDPE	100,000 t	(as comparable to PLA)
Air pollution		
CO	1084.06 t	Eco-profiles of the European Plastic Industry
SO_2	265.43 t	Eco-profiles of the European Plastic Industry
NO_2	206.08 t	Eco-profiles of the European Plastic Industry
CO_2	133,720 t	Eco-profiles of the European Plastic Industry
CH_4	1,195.3 t	Eco-profiles of the European Plastic Industry
Energy use		
Electricity	704 TJ	Eco-profiles of the European Plastic Industry
Fuel oil	1,015 TJ	Eco-profiles of the European Plastic Industry

Air pollution and energy use values are transferred from the Eco-profiles of the European Plastic Industry for crude oil, naphtha, ethylene, and HDPE. The gate-to-gate impact of each product can be obtained by subtracting the cradle-to-gate eco-profile of each product's raw materials from the cradle-to-gate eco-profile of the product itself. The equations below show the gate-to-gate calculations for HDPE and ethylene.

HDPE (gate-to-gate) = HDPE (cradle-to-gate) – Ethylene (cradle-to-gate)
Ethylene (gate-to-gate) = Ethylene (cradle-to-gate) – Naphtha (cradle-to-gate)
Naphtha (gate-to-gate) = Naphtha (cradle-to-gate) – Crude oil (cradle-to-gate)

CO_2 emission is the summation of energy use (electricity and fuel oil) plus air emissions. These air emissions are from fuel combustion and chemical reactions from all steps of the production process. In this research, fuel oil use is assumed to be representative of fuel use (the same assumption used in the PLA energy calculations).

Since the production technology of HDPE has been developed for more than 60 years (since 1951), it is now at a mature stage and is therefore relatively energy efficient. As a result, it is expected that the HDPE production process should require less energy (for each tonne of product) than the production of PLA (which is still in its embryonic stage).

Table 13. Cost and benefit of HDPE production from naphtha

	USD/kg HDPE
Direct cost	
1. Production cost (a)[a]	0.77
Indirect cost [b]	
1. CO_2 emission (b)[c]	0.124
2. CH_4 emission (c)	0.013
3. CO emission (d)	0.001
4. SO_2 emission (e)	0.003
5. NO_2 emission (f)	0.002
Total indirect cost (g) = (b)+(c)+(d)+(e)+(f)	0.143
Total cost (a) + (g) = (h)	0.913
Benefit [d]	1.43

Note: 1 USD = 0.8 Euro, as of 25 August, 2010

[a] See in Appendix 1

[b] Environmental cost evaluated from the EPS model developed in Sweden. The external cost of air pollutants are as listed: CO_2 USD 40/t CO_2, CH_4 USD 1070/t CH_4, NO_2 USD 840/t NO_2, SO_2 USD 1300/t SO_2, CO USD 130/t CO.

[c] CO_2 emission factor of electricity is 140 tCO_2/TJ while that of fuel oil is 77.4 tCO_2/TJ.

[d] The benefit of HDPE is the average domestic price of HDPE (Jan-Aug 2010) sourced from the Thai plastic industry association.

6.2 PLA Production Process and Input Data

PLA is a transparent plastic produced from glucose. The only commercial technology used for the production of PLA bioplastic is called the Cargill Dow process. This is the process used by NatureWorks and is the one assessed in this study.

In this research, two PLA production scenarios are considered. The first scenario involves the production of PLA using cassava root as the raw material. This is then turned into cassava starch, which is then processed into glucose, and finally into PLA. The second scenario starts with the production of glucose from cassava starch and then continues as per Scenario 1.

6.2.1 Scenario 1

As shown in Figure 13, in Scenario 1 cassava roots are used as feedstock to produce PLA resins. Cassava root produced in Thailand has 25% by weight of starch content, which can be converted to lactic acid with the weight ratio of 1.3 to 1 (TTSA 2010). Indeed, the expected production capacity of PLA in Thailand has been estimated by the NIA from the quantity of cassava the country produces (Suppasri and Sermcheep 2010).

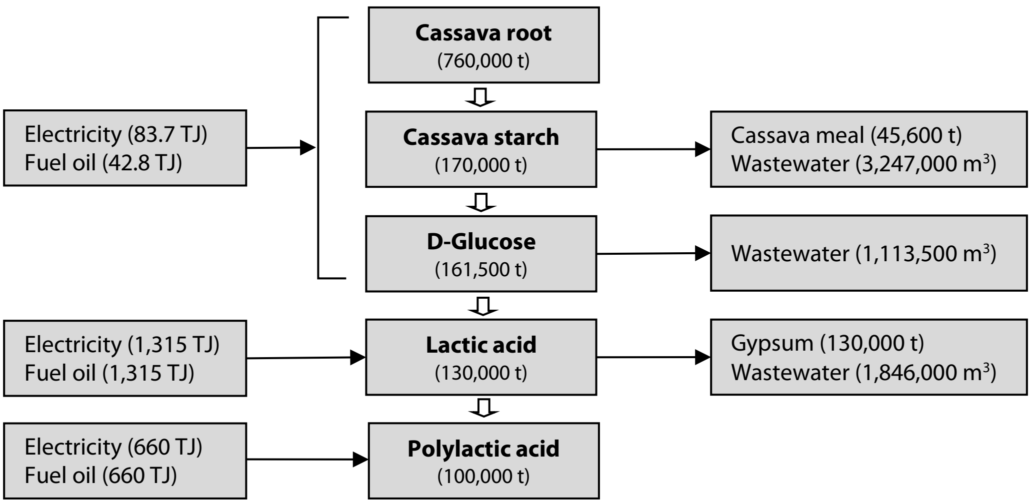

Figure 13. Mass and energy flow for PLA production from cassava root (Scenario 1)

In this scenario, cassava starch is transformed into glucose, then to lactic acid, and finally to PLA. Cassava meal and gypsum are the two main by-products. In the whole production process, certain amounts of wastewater are also produced.

According to Chavalparit and Ongwandee (2009), the quantity of wastewater produced from cassava starch production is about 19.1 m^3/ton. However, there is no published information available regarding the quantity of wastewater produced from the production of glucose from cassava starch. Interviews with plant owners showed that approximately 27 m^3 of water is used per tonne of sugar during the conversion of cassava roots to sugar. The quantity of wastewater produced in the fermentation process (when cassava starch is converted to sugar) is, therefore, the net of 1,113,000 m^3. Moreover, the process of lactic acid production from D-Glucose consumes 14.2 m^3 of water per kilogram of lactic acid produced; it is assumed that this is also the amount of wastewater discharged (Johansson 2005).

In terms of energy use, according to Vink *et al.* (2003), the amount of energy needed to convert dextrose (D-glucose) to lactic acid and lactic acid to PLA is 26.3 MJ and 13.2 MJ per kilogram of PLA, respectively. However, the ratio of energy sources was not specified in the study.

In this study, an assumption was made that 50% of the energy used comes from electricity and 50% from fuel oil. To calculate the overall energy used to convert cassava root to PLA, the amount of energy used in the process of dextrose production (cassava root to D-Glucose) was added. However, there is no published information on the energy used to produce D-Glucose from cassava in Thailand. To get this information, an interview was conducted with a PLA plant owner. The referent plant produces glucose from cassava root and has a production capacity of 300 t of sugar per day. The production of D-Glucose from cassava consumes 144kWh of electricity and 6.67 L of fuel oil per tonne of sugar produced.

6.2.2 Scenario 2

Sale of cassava meal is the main indirect benefit produced in the previous scenario. However, in that scenario, this benefit does not go directly to the PLA producers but to the cassava starch supplier. As a consequence, Scenario 2 focuses on the advantages that would accrue to someone investing in PLA production. This is done to provide more information on whether it would be worth investing in PLA production in Thailand. Figure 14 sets out the mass and energy flow for PLA production in Scenario 2.

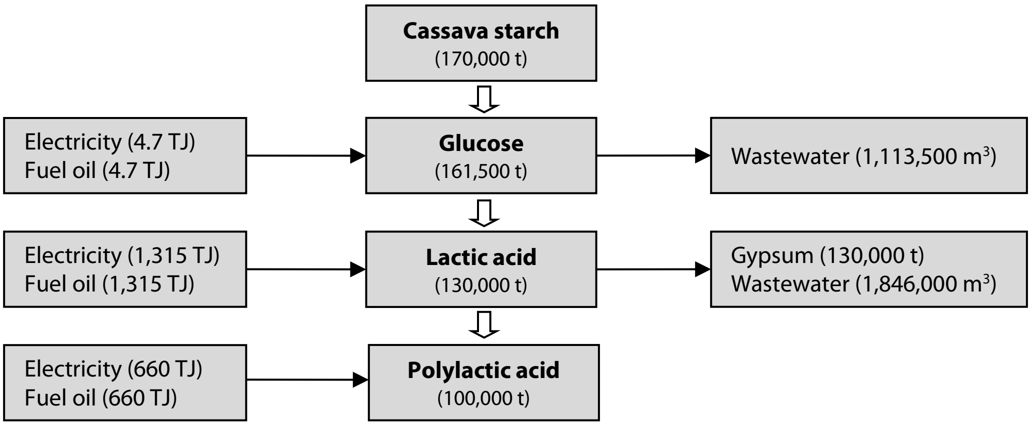

Figure 14. Mass and energy flow for PLA production from cassava starch (Scenario 2)

Scenario 2 is a plausible approach within the Thai context because a PLA producer is likely to use cassava starch as a raw material. It is therefore, assumed that cassava starch is purchased as the raw material of PLA production. As shown in Figure 14, cassava root and cassava starch production are removed from the energy and mass flow diagram of PLA production. Therefore, their by-product (cassava meal) and wastewater are also eliminated from any cost and benefit calculations. According to Vink *et al.* (2003), the energy and fuel used in the production of D-Glucose are not specifically identified. These values are assumed to be equal to 0.047 MJ/kg PLA, while other values of lactic acid and PLA production in this diagram are similar to the first scenario.

6.3 Cost of PLA Production

Aside from the financial costs (or the direct costs) that are typically assessed in the feasibility study of a project, environmental costs (or indirect costs) are also accounted for in this study. Therefore, the cost of PLA production is be divided into two parts: direct costs and indirect costs. These are carefully scrutinized in the following two sub-sections.

6.3.1 Direct costs of PLA production

Currently, no information on the production costs of PLA from cassava root is publicly available. This study, therefore, used the estimated cost of PLA produced from US corn using the Cargill Dow process in a plant with a capacity of 140,000 t/year. This estimated cost is between USD 1.97 and USD 2.42/kg of PLA (Shen *et al.* 2009). The yield of corn to PLA resin is 1.74 kg corn per kilogram of PLA (Vink *et al.* 2003). The difference in the production costs mainly comes from the cost of starch production which depends on the type of crop used. Basically, there are two PLA production routes: ring-opening of lactide and direct polymerization of lactic acid. However, only the ring-opening of lactide has been recognized and commercialized. Thus, the process of sugar conversion to PLA is a well-known technology. The process of making PLA from corn and cassava is similar and uses the same pathway (ring-opening of lactide), even though its raw materials come from different crops.

For Scenario 1, the total cost of PLA production includes an investment cost and an operating cost. In order to calculate the total cost of PLA production, the formula below is applied:

Total production cost of PLA from cassava =
total production cost of PLA from corn − production cost of corn − production cost of corn starch + production cost of cassava starch

In Scenario 2, the price of corn starch is replaced by the price of cassava starch. In order to calculate the cost of PLA production starting from cassava starch, the formula below is applied:

Total production cost of PLA from cassava =
total cost of PLA from corn − price of corn starch + price of cassava starch

For Scenario 1, the PLA production cost from cassava (conversion of cassava root to PLA resin) was the cost of PLA production from corn which is USD 2.2/kg of PLA, minus the production cost of corn and corn starch, and plus the production cost of cassava starch. The cost of US corn production is USD 0.2436/kg of PLA. The cost of corn starch production (ready-to-use corn to starch) is USD 0.0052/kg of PLA while the cost of cassava starch production in Thailand is USD 0.30/kg of PLA. For Scenario 2, the average price of corn starch (EXIM 2009) and cassava starch (TTSA 2010) is USD 0.68 and USD 0.94/kg, respectively. Therefore, the production cost of PLA from cassava for Scenario 1 is USD 2.25/kg PLA and for Scenario 2 is USD 2.46/kg of PLA.

According to news published in the Bangkok Post dated the 27^{th} December 2010, the investment cost of PLA production is approximately USD 330 million. This cost is for licensing the NatureWorks™ technology to produce 100,000 t/year. Thus, the investment cost of PLA production, annualized by a government bond rate of 1.29% over the 25 years of the project's life time, is USD 0.16/kg of PLA. As a result, the total production cost of PLA production for Scenario 1 is USD 2.41/kg of PLA and USD 2.62/kg of PLA for Scenario 2. These results are shown in Table 15.

6.3.2 Indirect cost of PLA production

The environmental costs (indirect costs) of PLA production comprise two main cost items: the cost of the CH_4 emissions from wastewater and the cost of the CO_2 emission caused by electricity and fuel consumption.

The calculation of CH_4 emissions from wastewater was adapted from the Project Design Document (PDD) for Clean Development Mechanism (CDM): #2556, #2645 and #2678. The calculation was based on the assumption that wastewater treatment was carried out using an aerated lagoon with a COD removal capacity of 0.019 t/m^3, a B_0 of 0.8, and a MCF of 0.21. It was also assumed that there was no CH_4 emission from the sludge. Wastewater produced 0.19 t and 0.09 t CH_4/t of PLA for the first and second scenario, respectively.

In Scenario 1, CO_2 emissions from fuel oil and electricity were 1.56 t and 2.89 t CO_2/t of PLA, respectively; while those for Scenario 2 were 1.53 t and 2.77 t/t of PLA, respectively. The CO_2 emission factors used to make these calculations were 77.4 t CO_2/TJ for fuel oil and 0.5057 t CO_2/MWh or 140 t CO_2/TJ (DEDE 2010), respectively.

According to Shen *et al.* (2009), the carbon embedded in PLA is determined by PLA's molecular structure, which has a molecular weight of 566 kg per mol PLA (n=7,858). The CO_2 avoided from using renewable materials for PLA production is therefore 1.83 t CO_2/t of PLA. The summary of the environmental impacts of PLA production, namely CO_2 emission, CH_4 emission, and CO_2 avoided, are presented in Table 14.

Table 14. Environmental impacts of PLA production

Environmental impacts	Scenario 1 Cassava root to PLA (kg/kg PLA)	Scenario 2 Cassava starch to PLA (kg/kg PLA)
GHG emission		
a)CH_4 from wastewater	0.19	0.09
b) CO_2 from electricity	2.89	2.77
c) CO_2 from fuel oil	1.56	1.53
GHG avoided		
d) CO_2 avoided from renewable material	1.83	1.83
Net CH_4 emission	**0.19**	**0.09**
Net CO_2 emission (b+c-d)	**2.62**	**2.47**

The net of the CO_2 emissions from both scenarios are 2.62 and 2.47 t CO_2/t of PLA, respectively (Table 14). Finally, the production costs of PLA for Scenario 1 and 2 are USD 2.71 and USD 2.82/kg PLA, respectively (Table 15).

Table 15. Cost of PLA production from cassava

	Scenario 1 (USD[a]/kg PLA)	Scenario 2 (USD/kg PLA)
Direct cost		
1. Operating cost of PLA production [b]	2.25	2.46
2. Investment cost of PLA production	0.16	0.16
Total direct cost	***2.41***	***2.62***
Indirect cost [c]		
1. CH_4 emission	0.20	0.10
2. CO_2 emission	0.10	0.10
Total indirect cost	***0.30***	***0.20***
Total costs	**2.71**	**2.82**

[a] 1 USD = 0.8 Euro, as of 25 August, 2010

[b] cost of US corn production (corn plantation and harvest) = USD 0.14/kg US corn (USDA 2010); cost of US corn starch production (corn receiving, storage and milling) = USD 0.003/kg corn (Krishman *et al.* 2000); cost of cassava starch production in Thailand = USD 0.174/kg starch, including cost of fresh cassava root (USD 0.154/kg starch); and operating cost of USD 0.020/kg starch (Chavalparit and Ongwandee 2009).

[c] USD 40/t CO_2 and USD 1070/t CH_4 which were estimated from the EPS model developed in Sweden. The hypothesis in the adaption of the model to Thailand is that the willingness-to-pay (WTP) is proportional to the GDP per capita. The ratio of WTP Thailand and WTP Sweden is derived as 0.288. (Nguyen and Gheewala 2008)

6.4 Net Benefits of PLA Production from Cassava

As in the preceding section, the benefits of PLA production are categorized into two sub-sections: direct benefits and indirect benefits. Both are detailed below.

6.4.1 Direct benefits of PLA production

According to Wolf *et al.* (2005), the expected price of PLA in 2005 is USD 3.00/kg of PLA. This is nearly equal to the current PLA market price obtained from PTT in 2010. Therefore, the direct benefit from the PLA production used in this study (for both scenarios) is USD 3.00/kg of PLA.

6.4.2 Indirect benefits of PLA production

The indirect benefit of PLA production under Scenario 1 (sale of the cassava meal by-product) is USD 2.94/kg of PLA; the price of cassava meal is about USD 6.45/t (TTSA 2010). Gypsum, which is another by-product of the PLA production process, has a relatively low market value and is therefore not accounted for in this study.

The net benefit of the PLA production process is calculated by deducting total costs from total benefits. The net benefit is USD 3.23 and USD 0.18/kg of PLA for Scenario 1 and 2, respectively (Table 16).

Table 16. Cost-benefit analysis of PLA production (without CDM revenue)

	Scenario 1 (USD/kg PLA)	Scenario 2 (USD/kg PLA)
Direct cost		
1. Operating cost of PLA production	2.25	2.46
2. Investment cost of PLA production	0.16	0.16
Total direct cost	***2.41***	***2.62***
Indirect cost		
1. CH_4 emission	0.20	0.10
2. CO_2 emission	0.10	0.10
Total indirect cost	***0.30***	***0.20***
Total costs	**2.71**	**2.82**
Benefit		
1. Direct benefits - sale of PLA resin	3.00	3.00
2. Indirect benefits - sale of by-product (cassava meal)	2.94	-
Total benefits	**5.94**	**3.00**
Total net benefits (total benefits – total costs)	**3.23**	**0.18**

GHG emissions related to electricity consumption, fuel oil usage and wastewater treatment is found to be a key element in the overall environmental impact of the PLA production process. The aerated lagoon wastewater treatment system modeled in this study is commonly implemented in small- and medium-sized starch factories in Thailand. The aerated lagoon system produces biogas as CH_4 due to anaerobic activity, and this can be a cause of global warming. However, CH_4 emitted from wastewater treatment can be recovered using Upflow Anaerobic Sludge Blanket (UASB) technology. The recovered biogas can then be utilized as an energy source in the place of electricity or fossil fuel. The resulting carbon offset can then be sold as carbon credits under the CDM program.

The reduction of $CO_{2\,(eq)}$ emissions estimated from three CDM projects applied in starch wastewater treatment projects in Thailand was approximately 0.06 t $CO_{2\,(eq)}/m^3$ of wastewater or 3.72 t $CO_{2\,(eq)}$/t of PLA for Scenario 1 and 1.77 t $CO_{2\,(eq)}$/t of PLA for Scenario 2. Additionally, revenue from selling Certified Emission Reductions (CERs) can be added to total benefits (at a rate of 11.23 Euro/t $CO_{2\,(eq)}$). The net benefits of PLA production including CDM revenue are presented in Table 17. If CDM is implemented, then the production of PLA will be more attractive and competitive than the production of conventional plastics.

Table 17. Cost-benefit analysis of PLA production (with CDM revenue)

	Scenario 1 (USD/kg PLA)	Scenario 2 (USD/kg PLA)
Direct cost		
1. Operating cost of PLA production	2.25	2.46
2. Investment cost of PLA production	0.16	0.16
Total direct cost	***2.41***	***2.62***
Indirect cost		
1. CH_4 emission	0.20	0.10
2. CO_2 emission	0.10	0.10
Total indirect cost	***0.30***	***0.20***
Total costs	**2.71**	**2.82**
Benefit		
1. Direct benefits - sale of PLA resin	3.00	3.00
2. Indirect benefits - sale of by-product	2.94	-
3. Revenue from CDM*	0.06	0.03
Total benefits	**6.00**	**3.03**
Total net benefits (total benefits – total cost)	**3.29**	**0.21**

* Selling price of CERs = 11.23 Euro/t $CO_{2\,(eq)}$ or USD 15.27/t $CO_{2\,(eq)}$ (TGO 2011).

Comparisons of the production costs and benefits of PLA and HDPE production cost are presented in Tables 18 and 19. As shown in Table 18, the net benefit of PLA production under Scenario 1 is USD 3.23/kg of PLA. This is 6.8 times larger than the net benefit of HDPE production. In contrast, the comparison of PLA production under Scenario 2 and HDPE production in Table 19 shows the net benefit of HDPE production is higher than that of PLA by USD 0.29/kg of PLA.

Table 18. Cost-benefit analysis of PLA production (Scenario 1) compared to HDPE production

Scenario 1		PLA production (USD/kg PLA)	HDPE production (USD/kg HDPE)
Direct cost	Production cost	2.25	0.77[a]
	Investment cost	0.16	0.05
Indirect cost	GHG emissions	0.30	0.144[b]
Direct benefits	Sale of product	3.00	1.43[c]
Indirect benefits	Sale of by-product	2.94	-
Net benefit		**3.23**	**0.47**

Table 19. Cost-benefit analysis of PLA production (Scenario 2) compared to HDPE production

Scenario 2		PLA production (USD/kg PLA)	HDPE production (USD/kg HDPE)
Direct cost	Production cost	2.46	0.77[a]
	Investment cost	0.16	0.05
Indirect cost	GHG emissions	0.20	0.143[b]
Direct benefits	Sale of product	3.00	1.43[c]
Net benefit		**0.18**	**0.47**

[a] Production cost = Investment cost + Operation cost

[b] Environmental cost or emissions evaluated from the EPS model developed in Sweden. These values were corrected by Nguyen and Gheewala (2008) using the ratio of WTP of Thailand to Sweden as 0.288. The external cost of air pollutants include USD 40/t CO_2, USD 1070/t CH_4, USD 840/t NO_2, USD 1300/t SO_2, and USD 130/t CO.

[c] The direct benefit of HDPE is the average domestic price of HDPE (TPIA 2010).

The difference in these results is mainly due to the different starting points of the two scenarios. In particular, Scenario 2 does not account for the sale of the cassava meal by-products, which means that it has a substantially lower net benefit than Scenario 1.

When the selling price of both PLA and HDPE resins are compared, it is interesting to note that PLA is almost two times more expensive than HDPE, even though the benefits of PLA resin are significantly lower. This can be explained by the fact that PLA investment costs are three times higher than those of HDPE. However, as PLA production technology is still in its initial development stages, there should be significant potential to improve the efficiency of PLA production, and so minimize its costs.

6.5 Net Present Value

As mentioned earlier in Section 6.2.2, this study aims to highlight the potential advantages that investing in the PLA sector might bring. Accordingly, Scenario 2 is chosen as the status quo for this study's NPV calculations. These calculations, which take both financial and environmental costs and benefits into account, were done to evaluate whether it is worthwhile to invest in PLA production in Thailand.

This study assumes a time horizon of 25 years. This will commit the PLA industry to the stream of expenditures shown in column (2) of Table 20. It will result in the series of benefits shown in column (3). The discount factor for a 1.29% real discount rate is shown in column (4). The present value (PV) cost for each of the 25 years, presented in column (5), is calculated by multiplying column (2) by column (4). The PV benefit for each of the 25 years, presented in column (6), is calculated by multiplying column (3) by column (4).

From Table 20, the sum of column (5) is the total PV of costs and the sum of column (6) is the total PV of benefits. NPV is the difference between the sum of discounted benefits and the sum of discounted costs. The NPV for the 25-year lifetime of the project is positive and has a value of USD 4.87/kg of PLA.

Table 20. Present values of costs and benefits for PLA production in Scenario 2, USD/kg of PLA

Year (1)	Expected yearly cost* (2)	Expected yearly benefit (3)	Discount factors for 1.29%** (4)	PV of costs (5)	PV of benefits (6)
1	2.82	3	1.0000	2.8150	3.0000
2	2.8136	3	0.9873	2.7748	2.9618
3	2.8075	3	0.9747	2.7353	2.9241
4	2.8016	3	0.9623	2.6964	2.8868
5	2.7959	3	0.9500	2.6582	2.8501
6	2.7905	3	0.9379	2.6206	2.8138
7	2.7852	3	0.9260	2.5837	2.7779
8	2.7802	3	0.9142	2.5474	2.7426
9	2.7754	3	0.9025	2.5117	2.7076
10	2.7708	3	0.8910	2.4765	2.6731
11	2.7664	3	0.8797	2.4420	2.6391
12	2.7621	3	0.8685	2.4080	2.6055
13	2.7580	3	0.8574	2.3745	2.5723
14	2.7541	3	0.8465	2.3416	2.5395
15	2.7503	3	0.8357	2.3092	2.5072
16	2.7467	3	0.8251	2.2773	2.4753
17	2.7433	3	0.8146	2.2460	2.4437
18	2.7399	3	0.8042	2.2151	2.4126
19	2.7367	3	0.7940	2.1847	2.3819
20	2.7337	3	0.7839	2.1548	2.3516
21	2.7307	3	0.7739	2.1253	2.3216
22	2.7279	3	0.7640	2.0964	2.2920

Table 20 continued

Year (1)	Expected yearly cost* (2)	Expected yearly benefit (3)	Discount factors for 1.29%** (4)	PV of costs (5)	PV of benefits (6)
23	2.7252	3	0.7543	2.0678	2.2629
24	2.7226	3	0.7447	2.0397	2.2340
25	2.7201	3	0.7352	2.0120	2.2056
Total	**69.0584**	**75**	**21.5276**	**59.7141**	**64.5827**
				NPV	**4.8686**

* Investment cost was recalculated using a depreciation rate of 4% each year. (Total cost = Investment cost + Operation cost).
** Real discount rate = Nominal discount rate – General inflation rate = Thailand's Government Bond Yield for 30 Year Notes – General Inflation Rate = 4.29% – 3.00% = 1.29%
Source: Bank of Thailand 2011

In addition, three more scenarios were applied in this study: a) Option 1 incorporates expected PLA price developments (i.e., a change in benefits); b) Option 2 incorporates a change in the cost of PLA due to technological developments; and c) Option 3 incorporates a change in both the benefits and costs of PLA. The first option is based on the expected price developments of PLA over the project time period. According to Wolf *et al.* (2005), the price of PLA should fall by approximately 0.7% each year due to further improvements in price competiveness. Table 21 shows the PVs of the costs and benefits of PLA production, taking into account expected price developments (i.e., the situation modeled in Option 1). The benefit in column (3) of this table therefore shows a decrease in selling price as a proxy for PLA benefits. The NPV of this option shows a negative sign.

Table 21. Present values of costs and benefits for PLA with expected price developments, USD/kg of PLA

Year (1)	Expected yearly cost* (2)	Expected yearly benefit (3)	Discount factors for 1.29%** (4)	PV of costs (5)	PV of benefits (6)
1	2.82	3.00	1.0000	2.8150	3.0000
2	2.8136	2.98	0.9873	2.7748	2.9412
3	2.8075	2.96	0.9747	2.7353	2.8835
4	2.8016	2.94	0.9623	2.6964	2.8267
5	2.7959	2.92	0.9500	2.6582	2.7709
6	2.7905	2.90	0.9379	2.6206	2.7161
7	2.7852	2.88	0.9260	2.5837	2.6622
8	2.7802	2.85	0.9142	2.5474	2.6092
9	2.7754	2.83	0.9025	2.5117	2.5572
10	2.7708	2.81	0.8910	2.4765	2.5061
11	2.7664	2.79	0.8797	2.4420	2.4558
12	2.7621	2.77	0.8685	2.4080	2.4065
13	2.7580	2.75	0.8574	2.3745	2.3579
14	2.7541	2.73	0.8465	2.3416	2.3103
15	2.7503	2.71	0.8357	2.3092	2.2634
16	2.7467	2.69	0.8251	2.2773	2.2174
17	2.7433	2.67	0.8146	2.2460	2.1722
18	2.7399	2.65	0.8042	2.2151	2.1278
19	2.7367	2.63	0.7940	2.1847	2.0842
20	2.7337	2.60	0.7839	2.1548	2.0413
21	2.7307	2.58	0.7739	2.1253	1.9992
22	2.7279	2.56	0.7640	2.0964	1.9578
23	2.7252	2.54	0.7543	2.0678	1.9171
24	2.7226	2.52	0.7447	2.0397	1.8772
25	2.7201	2.50	0.7352	2.0120	1.8380
Total	**69.0584**	**68.75**	**21.5276**	**59.7141**	**59.4992**
				NPV	**-0.2149**

Option 2 is considered because several companies have been developing their bioplastic production technologies. As a result of this development work, Purac has publically indicated that its technology could lower the production costs of lactic acid production. The reduction could be equivalent to 40% of PLA production costs by the year 2016 (Bohlmann 2007). As mentioned previously, the production of lactic acid accounts for 45% of total PLA production costs (PROBIP 2009 in Shen *et al.* 2009). Thus, the production cost of lactic acid is USD 1.10 /kg PLA after the technological innovation has taken place. Table 22 shows the effect of this potential technological development as a reduction in the cost of PLA production, as shown in column (3). As a result, the NPV of this option is USD 15.65/kg of PLA, which is higher than the status quo's NPV of USD 4.87/kg of PLA.

Table 22. Present values of costs and benefits for PLA with technological developments, USD/kg PLA

Year (1)	PV of investment costs (2)	PV of operation cost* (3)	Benefit (4)	PV of total cost (5)	PV of benefits (6)
1	0.1600	2.655	3	2.8150	3.0000
2	0.1536	2.5776	3	2.7312	2.9618
3	0.1475	2.5016	3	2.6491	2.9241
4	0.1416	2.4273	3	2.5688	2.8868
5	0.1359	2.3544	3	2.4903	2.8501
6	0.1305	2.2830	3	2.4134	2.8138
7	0.1252	2.2130	3	2.3382	2.7779
8	0.1202	2.1443	3	2.2646	2.7426
9	0.1154	2.0772	3	2.1926	2.7076
10	0.1108	2.0113	3	2.1222	2.6731
11	0.1064	1.9468	3	2.0532	2.6391
12	0.1021	1.8837	3	1.9858	2.6055
13	0.0980	1.8218	3	1.9198	2.5723
14	0.0941	1.7612	3	1.8553	2.5395
15	0.0903	1.7018	3	1.7922	2.5072
16	0.0867	1.6437	3	1.7304	2.4753
17	0.0833	1.5868	3	1.6700	2.4437
18	0.0799	1.5310	3	1.6110	2.4126
19	0.0767	1.4764	3	1.5532	2.3819
20	0.0737	1.4230	3	1.4967	2.3516
21	0.0707	1.3707	3	1.4414	2.3216
22	0.0679	1.3195	3	1.3874	2.2920
23	0.0652	1.2694	3	1.3345	2.2629
24	0.0626	1.2202	3	1.2828	2.2340
25	0.0601	1.1722	3	1.2323	2.2056
Total	**2.5584**	**46.3730**	**75**	**48.9314**	**64.5827**
				NPV	**15.6513**

* Total cost = Investment cost + Operation cost where Operation cost = Production cost + Indirect cost

Note: Percent share of lactic acid production cost in PLA production = 45% (PROBIP 2009 in Shen *et al.* 2009)

Option 3 assesses the effect of realistic future changes in both costs and benefits. As shown in Table 23, these changes give an estimate of a positive NPV (USD 10.57/kg of PLA). This finding reflects the impact of expected changes in the market price of PLA alongside the impact of expected technological improvements, over 25 years. This finding shows that it would be worthwhile for policymakers to step up efforts to launch a bioplastic plant in Thailand.

Table 23. Present values of costs and benefits for PLA production combining Options 1 and 2, USD/kg of PLA

Year (1)	PV of Investment Costs (2)	PV of Operation Cost (3)	Benefit (4)	PV of Total Cost (5)	PV of Benefits (6)
1	0.1600	2.655	3	2.8150	3.0000
2	0.1536	2.5776	2.98	2.7312	2.9412
3	0.1475	2.5016	2.96	2.6491	2.8835
4	0.1416	2.4273	2.94	2.5688	2.8267
5	0.1359	2.3544	2.92	2.4903	2.7709
6	0.1305	2.2830	2.90	2.4134	2.7161
7	0.1252	2.2130	2.88	2.3382	2.6622
8	0.1202	2.1443	2.85	2.2646	2.6092
9	0.1154	2.0772	2.83	2.1926	2.5572
10	0.1108	2.0113	2.81	2.1222	2.5061
11	0.1064	1.9468	2.79	2.0532	2.4558
12	0.1021	1.8837	2.77	1.9858	2.4065
13	0.0980	1.8218	2.75	1.9198	2.3579
14	0.0941	1.7612	2.73	1.8553	2.3103
15	0.0903	1.7018	2.71	1.7922	2.2634
16	0.0867	1.6437	2.69	1.7304	2.2174
17	0.0833	1.5868	2.67	1.6700	2.1722
18	0.0799	1.5310	2.65	1.6110	2.1278
19	0.0767	1.4764	2.63	1.5532	2.0842
20	0.0737	1.4230	2.60	1.4967	2.0413
21	0.0707	1.3707	2.58	1.4414	1.9992
22	0.0679	1.3195	2.56	1.3874	1.9578
23	0.0652	1.2694	2.54	1.3345	1.9171
24	0.0626	1.2202	2.52	1.2828	1.8772
25	0.0601	1.1722	2.50	1.2323	1.8380
Total	**2.5584**	**46.3730**	**68.75**	**48.9314**	**59.4992**
				NPV	**10.5678**

6.6 Sensitivity Analysis

Further analysis was carried out to illustrate the sensitivity of the possible NPV presented in Table 23. This is because the result of the analysis may be changed due to changes in factors such as interest rates. Thailand has experienced high and low rate of interest due to various economic upheavals.

As mentioned in Section 6.5, the Government Bond Yield for 30 Year Notes (4.29%) was used as the nominal discount rate; this makes the real discount rate approximately 1.29%. This real discount rate of 1.29% is considered to be low as a base rate, due to expected levels of inflation of 3%. In addition, the Thailand Government Bond high of 6.72% that occurred in 2005 (www.tradingeconomics.com) shows that there is a possibility of an increase in the government bond rate. This is significant, as using an artificially low discount rate for project evaluation can make future generations worse off.

Therefore, testing was done over a range of 4.29 to 8.29% in nominal terms or a range of 1.29 to 5.29 in real terms. Three nominal discount rates were used in the calculation of NPV, namely 4.29% (as status quo), 6.29%, and 8.29%.

The NPVs for PLA production (over a 25-year life time) are presented in Table 24. With the status quo, the NPVs decrease gradually as the discount rates increase. When the 6.29% nominal discount rate is applied, the change of NPV for PLA production will be +3.4509% instead of 4.8686% with the discount rate at 4.29%. If 8.29% discount rate is applied, the change of NPV for PLA production will be +2.4157%.

Table 24. Costs and benefits of the various options, USD/kg of PLA

Options	Discount rates*	PV - benefit	PV - cost	NPV
Status quo - No change in operation cost and benefit[1]	4.29%	64.5827	59.7141	4.8686
	6.29%	52.2552	48.8043	3.4509
	8.29%	43.2529	40.8372	2.4157
Reduction in benefit only[2]	4.29%	59.4992	59.7141	-0.2149
	6.29%	48.5049	48.8043	-0.2994
	8.29%	48.7555	40.8372	-0.3054
Reduction in cost only[3]	4.29%	64.5827	48.9314	15.6513
	6.29%	52.2552	40.8494	11.4059
	8.29%	43.2529	34.8541	8.3998
Reduction in cost and benefit[4]	4.29%	59.4992	48.9314	10.5678
	6.29%	48.5049	40.8494	7.655
	8.29%	48.7555	34.8541	5.5781

* The discount factor is calculated as $1/(1 + i)^t$ where *i* is the real interest rate and *t* is the year. Note: Real interest rate = the government bond – inflation rate of 3% (Assume interest rates for government bond are 4.29%, 6.29%, and 8.29%, respectively.)
[1]refers to Scenario 2 without additional options introduced
[2]refers to Option 1 (change in benefits because of expected price developments)
[3]refers to Option 2 (change in costs because of technological developments)
[4]refers to Oction 3 (combination of Options 1 and 2)

These results show that all assumptions are good for investment (i.e., they have an NPV > 0), except for the option in which PLA prices change over time. The results also show that, even though NPVs become smaller as the discount rate increases (as predicted theoretically), the result is insensitive to potential changes of all discount rate assumptions.

7.0 CONCLUSIONS

The costs of PLA production from cassava calculated in this study were transferred from the *Gate-to-Gate* costs of PLA production from corn. The cost calculations included direct costs (production costs and investment costs) and indirect environmental costs.

The cost of PLA production starting from cassava starch to PLA resin is USD 2.82/kg of PLA, which is larger than from the production cost of PLA resin starting from cassava root (i.e., USD 2.71/kg of PLA).

The production of PLA from cassava root provides cassava meal as a by-product. Taking into account the benefits that can be obtained from selling this cassava meal, the net benefits of PLA production from cassava root is USD 3.23/kg of PLA. This is 18 times higher than it would be if the cassava meal was not sold.

The net benefits of PLA production (including sales of cassava meal) are 6.8 times larger than the net benefits of HDPE production. However, without sales of cassava meal, the net benefits of PLA production are less than those of HDPE production.

The NPV of PLA production (cassava starch to PLA resin) calculated over a 25-year life time, with a real discount rate of 1.29%, is positive. Even when potential PLA price changes and technological developments are taken into account, the NPV is still positive. The sensitivity analysis result indicates that the NPV of PLA production is insensitive to an increase in real discount rates (1.29 to 5.29%).

With respect to environmental issues, the CO_2 emissions that are avoided by using cassava as a renewable raw material for PLA production amount to 1.83 kg CO_2/kg of PLA. However, this saving is less than the CO_2 emissions that result from the electricity, fuel oil and wastewater treatment used during the production process.

This study indicates that HDPE production has a better environmental performance, in terms of energy efficiency and environmental pollution, than PLA production. This finding can be explained by the different levels of development and 'maturity' of the technology used to manufacture the two types of plastic. Accordingly, it is clear that there is significant scope for improvements to be made in the PLA production and waste management process; in particular, energy efficiency can be enhanced, biomass waste can be utilized as fuel and GHG can be recovered from the wastewater treatment process and used as an energy source.

Even though the environmental impact of PLA found in this study is higher than that of HDPE, it should be noted the embedded carbon in HDPE is not released until the final state of its life cycle (waste treatment). Consequently, further study is required to investigate the entire life cycle of both materials in order to evaluate their respective total environmental impact.

8.0 POLICY RECOMMENDATIONS

Currently, the price of bio-based plastic is approximately twice that of conventional plastics produced from petroleum. Bulk production could reduce the production costs of bioplastics; however, an increase in production capacity depends on the demand for bioplastics in the marketplace. Looked at from another point of view, the environmental costs of bioplastics will be lower than that of conventional plastics, if the net social benefits of PLA production is addressed.

This study indicates that the wastewater treatment process used in cassava starch production is a major source of GHG emissions, as is the electricity and fuel oil used. This means that, if the net social benefits of PLA production are to be improved, these environmental burdens must be intensively reduced. Cassava starch and sugar production should therefore be considered as potential targets for a pollution control program.

Clean technology (CT) or waste minimization programs, coupled with a 4Rs (Reduce, Reuse, Recycle and Recover) strategy, should be established and introduced to cassava starch and sugar production plants. CT implementation should lead to a reduction in the use of natural resources, electricity and fuel, and a drop in the amount of waste produced. New biogas recovery systems should also be installed as part of the wastewater treatment systems of such plants. Such a move would reduce GHG emissions to the atmosphere, while the biogas captured could be converted to energy. The resulting reduction in the GHG emissions of the PLA production process could then be converted to carbon credits and sold to the carbon market. Another option is to set up carbon tax in order to reduce the environmental burden of bioplastic production.

According to the results of this research, the benefits that can be obtained from PLA production (cassava starch to PLA resin) are less than those of HDPE by USD 0.29/kg of PLA. To encourage PLA production in Thailand, the government should provide some attractive policies, such as subsidy programs, to bioplastic investors. The necessary policies to support PLA production must mitigate the existing technical and environmental burdens and be based on available technology. The Thai government should legislate a new Royal Decree or act to encourage investment in bioplastic production in all relevant upstream, intermediate and downstream sectors such as starch or sugar production, lactic acid production, and PLA production.

Recently, the Fiscal Policy Office of the Ministry of Finance has drawn up the law of Fiscal Measures for the Environment. This law covers: environmental taxation, product taxation, pollution treatment fees, and emission permits. The cabinet has approved this law as of October, 2010 (FPO 2010). The pollution fee for wastewater is set at THB 10,000/t of pollutants. The pollution fee for air pollution is THB 2,500/t of pollutants. This law can be implemented as a tool to control the emissions of the PLA production process and as a driver to encourage investment in more environment-friendly technology for bioplastic production.

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Appendix 1. HDPE Cost calculation

Total cost of HDPE (from Naphtha) = Total cash cost + Depreciation
= (702) + (68)
= USD 770/t

Total cash cost = Variable cost + Direct cost + Allocated cost = USD 702/t

Variable cost = Monomer (ethylene) and Comonomer + Other raw material + Utilities
= USD 600/t + USD 30/t + USD 30/t
= USD 660/t

Direct costs = USD 21/t

Allocated costs = USD 21/t

Depreciation = USD 68/t

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