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Life Cycle Energy and Environmental Analysis Study of a Model Biorefinery in Thailand

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There is commercial production of biofuels and biochemicals in Thailand. Yet there are no biorefineries at present. This study aims to evaluate the life cycle energy and environmental impacts associated with the production of biofuels and biopolymers for a model biorefinery in Thailand. Since there is currently no biorefinery in the country, secondary data sources from existing bioethanol and biopolymer plants were used for life cycle analysis (LCA). Sugarcane and cassava were chosen as feedstocks for the proposed biorefinery to produce bioethanol and polylactic acid (PLA). The system boundary was defined as cradle-to-gate with LCA methodology based on ISO 14040 series. Data were analyzed by using commercial LCA software, SimaPro 7.1, with Eco-Indicator 95 and CML 2 baseline 2000. The biorefinery system was modeled and its performance was evaluated for several factors such as fuel and biopolymer production, raw materials consumption, and total revenue generation for five scenarios. The results indicated that the biorefinery showed better performance in both global warming potential (GWP) and energy resources with increasing sugarcane usage. This was due to the use of bagasse and biogas as sources of fuel to generate electricity and steam by using a highly efficient electrical energy cogeneration process in the biorefinery. In contrast, increasing PLA production led to higher GWP and energy resource impacts due to high electricity and steam usage in the bioplastic production process. Finally, two Eco-efficiency parameters was developed in order to combine both environmental (GWP and energy resources) and economic (revenue) aspects by using average revenue gained and average impact associated. Among five scenarios studied, the results showed that S4 – high sugarcane usage and ethanol production – was the best scenario as it has higher eco-efficiency in both aspects.

1. Introduction

As the world is facing an energy crisis due to the rising price and shortage of fossil-based resources, the utilization of biomass-based alternative processes to produce biofuels, biochemicals and/or biomaterials could help reduce both energy resource and global warming problems by using various technologies. A biorefinery is a facility that integrates biomass conversion processes and equipments to convert biomass resources (e.g., cassava, sugarcane, wood, palm, etc.) into basic products like starch, sugar, cellulose and oil. The products can be transformed to value-added products such as fuels, chemicals, materials and energy. The biorefinery complex provides high-cost products from low-cost feedstocks due to the efficient use of resources and waste minimization, which consequently leads to maximizing benefits and profitability. Since Thailand has abundance in natural biomass resources, there is great potential for using these feedstocks in biorefineries to produce various bio-products. Currently, there is commercial production of biofuels and biopolymers in Thailand but there is no biorefinery complex. This study focuses on evaluating the energy and environmental impacts associated with the production of a biofuel (bioethanol) and biopolymer (polylactic acid) for a model biorefinery in Thailand. Sugarcane and cassava were chosen as feedstocks for the proposed of biorefinery. The scope of the research covered inventory data collection (raw materials, chemicals, energy, utilities, and emissions) for the production of bioethanol

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and polylactic acid (PLA) based on the cradle-to-gate approach. Since there is no biorefinery in the country, secondary data sources from existing bioethanol and PLA plants and current research were used for the life cycle analysis (LCA) based on the ISO 14040 series framework. The biorefinery model was created while the performance was evaluated for several factors such as fuel and biopolymer production, raw materials consumption, and total revenue generation by creating five scenarios. The results were analyzed by using commercial LCA software, SimaPro 7.1, with Eco-Indicator 95 and CML 2 baseline 2000 methods to identify the environmental burdens, in terms of energy resources and global warming impact (GWP). Finally, two Eco-efficiency parameters were developed to combine both environmental and economic aspects and used to find an optimal scenario from the scenarios created in this study. Suggestions for the development of a future biorefinery in Thailand, with sustainable biorefinery improvements, were also included.

2. Methodology

2.1 Goal and scope

The goal of this LCA study was to assess the energy and environmental impacts of the biorefinery model which produces bioethanol, polylactic acid (PLA), electricity and heat using sugarcane and cassava as feedstocks. The methodology used in this study was based on ISO14040 series. The inventory data were collected from secondary data sources (National Thai LCI database, previous works on LCA of biofuels and biopolymers production in Thailand, and selected references) and compiled by using commercial LCA software, SimaPro 7.1, with Eco-Indicator 95 and CML 2 baseline 2000 methods. Five scenarios were created by varying the ratio of raw materials (sugarcane and cassava) and products (bioethanol and PLA). The energy resource, environmental impacts, and generated revenue of all scenarios were compared.

2.2 Functional unit

The performance of the biorefinery model was evaluated for fuel and biopolymer production, raw materials consumption, and total revenue generation.

2.3 System boundary

The system boundary of the biorefinery covers feedstock cultivation, feedstock transportation, feedstock processing, ethanol conversion and PLA resin production as shown in Figure 1. The ethanol and PLA production capacities are estimated at 160 ton/day and 300 ton/day, respectively.

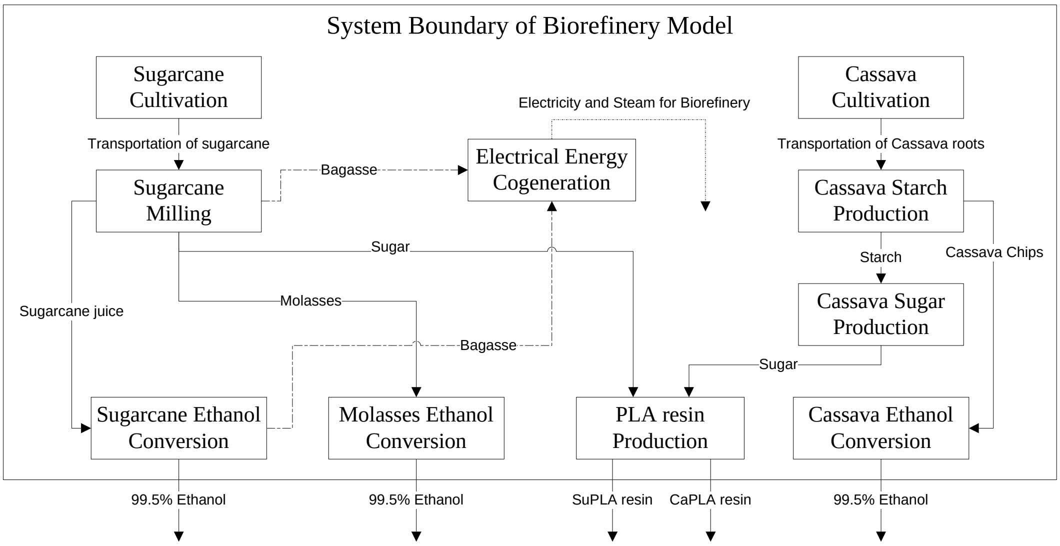

Figure 1: System boundary of the biorefinery model.

2.4 Sources of data

Table 1 shows the sources of the inventory data of the biorefinery model in Thailand within the system boundary shown in Figure 1 for all relevant input-output data including raw material consumption, energy consumption, product generation, air/water emissions, and waste generations.

Table 1: Sources of the inventory data used in this study

Phase	Items	Data source
Cassava cultivation*	Fertilizers, diesel, pesticides, lubricant oil, emission from fertilizing, etc.	Thailand LCI database, MTEC.
Sugarcane cultivation*	Fertilizers, pesticides, diesel, lubricant oil, emission from fertilizing, etc.	Thailand LCI database, MTEC.
Transportation	Diesel, emission to air	Thailand LCI database, MTEC,
Chips production	Diesel, emission to air	Silalertruksa and Gheewala (2011), Calculations and estimations.
Cassava starch and sugar production	Energy, chemicals, emission to air, biogas generation	Thailand LCI database, MTEC.
Sugarcane milling	Energy, chemicals, water, emission to air, water, and soil	Thailand LCI database, MTEC.
Electrical energy cogeneration**	Electricity and steam generation, emission to air	Tossanaitada and Tia (2008), Calculations and estimations.
PLA resin production	Energy, chemicals, emission to air and water	Groot and Boren (2010), MTEC study.
Cassava ethanol conversion	Energy, water, chemical, emission to air, water, and soil, DDGS and biogas generation	Thailand database, KAPI (2008)
Molasses ethanol conversion	Energy, water, chemical, emission to air, water, and soil, biogas generation	Thailand database, KAPI (2008)
Sugarcane ethanol conversion	Energy, water, chemical, emission to water, vinasse generation	Ometto et al. (2010)

* Excludes CO_2 uptake

** Highly efficient high pressure boiler

2.5 Scenarios studied

Five scenarios (S1-S5) for the biorefinery model, shown in Table 2, were created by varying the ratio of raw materials (sugarcane, and cassava) and products (ethanol, and PLA) based on a fixed biorefinery production capacity (ethanol 160 t/d and PLA 300 t/d). It was assumed that production would always be at least 70% of total capacity in all scenarios. This corresponded to the overall production of ethanol and PLA (combined) of 391 t/d or 85% capacity which was a target for optimization between environmental impacts and revenue. Revenue ($/d) was calculated using the current average price of the ethanol and PLA products in Thailand.

Table 2: Scenarios of biorefinery model under study

Scenarios	**S1**	**S2**	**S3**	**S4**	**S5**
Feedstocks					
Sugarcane/Cassava (wt. %)	80/20	60/40	40/60	80/20	80/20
Sugarcane used (t/d)	3,081	2,085	1,272	3,130	3,057
Cassava used (t/d)	772	1,394	1,902	765	765
Products					
Ethanol/PLA (wt. %)	35/65	35/65	35/65	41/59	29/71
Ethanol produced (t/d)	136	136	136	160	112
PLA produced (t/d)	255	255	255	231	279
Sugarcane based ethanol, SuE (t/d)	11	35	55	19	3
Molasses based ethanol, MoE (t/d)	23	12	3	23	24
Cassava based ethanol, CaE (t/d)	102	89	78	118	85
Sugarcane based PLA, SuPLA (t/d)	237	126	35	231	245
Cassava based PLA, CaPLA (t/d)	18	129	220	0	34
Revenue ($/d)	1,081,808	1,060,585	1,042,967	1,037,321	1,126,387

3. Results and discussion

Based on the biorefinery model developed in this study (Figure1), sugarcane and cassava were co-utilized as feedstocks. Operation of a sugarcane plantation and harvesting were included in sugarcane cultivation process. After harvest, this sugarcane was transported to a sugar mill to extract sugarcane juice. The juice was then converted into sugar and molasses. These two products were used as raw materials for production of sugarcane-based PLA (SuPLA) and molasses-based ethanol (MoE). Moreover, some sugarcane juice could be used to produce sugarcane-based ethanol (SuE) directly by the sugarcane ethanol conversion process. After cultivate and transport of cassava, this cassava was divided into two parts. The first part was transformed to sugar via cassava starch and sugar production processes. This sugar was further used as the raw material for cassava-based PLA resin (CaPLA) by the PLA resin production process. The other part was chipped and used as a feedstock for cassava-based ethanol (CaE) production with dried distiller grains with solubles (DDGS) production line. Apart from the main feedstocks, bagasse produced from the sugar milling and sugarcane ethanol conversion process were used as fuel to generate electricity and steam for the biorefinery by using a highly efficient electrical and energy cogeneration process. All processes in the biorefinery model were divided into four stages include feedstock production, feedstock transportation, feedstock processing, and ethanol conversion / PLA resin production, as summarized in Table 3.

Table 3: Four major stages of the processes in the biorefinery model

Product	Feedstock production	Feedstock transportation	Feedstock processing	Ethanol conversion / PLA resin production
SuE	Sugarcane cultivation	Sugarcane transportation	-	Sugarcane ethanol conversion
MoE	Sugarcane cultivation	Sugarcane transportation	Sugar milling	Molasses ethanol conversion
CaE	Cassava cultivation	Cassava transportation	Cassava chips production	Cassava ethanol conversion
SuPLA	Sugarcane cultivation	Sugarcane transportation	Sugar milling	PLA resin production
CaPLA	Cassava cultivation	Cassava transportation	Cassava starch and sugar production	PLA resin production

Based on the stages and processes listed in Table 3, the life cycle inventory (LCI) was performed by collecting secondary data from existing bioethanol and biopolymer plants in Thailand and related studies. After LCI was completed, five scenarios were created. They were divided into two groups; Group 1 (S1, S2 and S3) was obtained by the varying ratio of the two feedstocks while Group 2 (S4, S1 and S5) was obtained by varying the ratio of the products. Then, the life cycle impact assessment (LCIA) was analyzed by using LCA software; SimaPro 7.1, in order to evaluate the performance of all five scenarios of the biorefinery model in terms of GWP impact (CML 2 baseline 2000) and energy resource impact (Eco-indicator 95) as discussed in the following sections.

3.1 Global warming potential (GWP)

In the feedstock processing stage; the major source of GWP came from electricity and steam consumption in the cassava starch and sugar production processes of CaPLA production. In contrast, environmental benefit (negative impact) was obtained in sugar milling, which was the feedstock processing stage for MoE and SuPLA production. This was due to the surplus electricity and steam produced, which could be used in other processes. This energy integration could help reduce GWP as seen in scenarios S5, S4, and S1 which had much higher SuPLA production than S2 and S3. Thus, S5, S4, and S1 had less GWP impact than S2 and S3, as shown in Figure 2a.

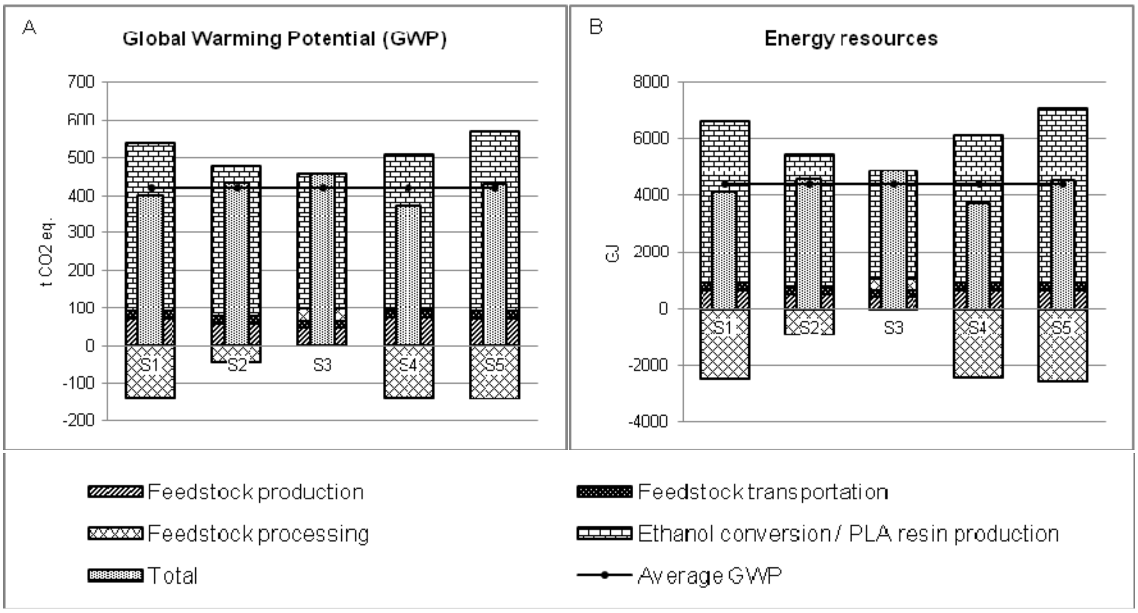

Figure 2: A) Global warming potential result by using CML 2 baseline 2000 and B) Energy resources results by using Eco-indicator 95 for each stage of five scenarios under study.

It can be seen that the ethanol conversion/PLA resin production stage contributed the highest GWP among all four stages (Figure 2a). In this stage, major GWP was also caused by electricity and steam consumption in PLA resin production. The molasses and cassava ethanol conversion processes were shown to be the second and third contributors, respectively, to GWP impact, even though, there was biogas produced from these processes which was used to generate electricity to compensate for the energy consumption in the processes. On the contrary, the sugarcane-based ethanol conversion process for SuE production was shown to have better performance in regards to GWP impact due to the generation of surplus electricity and steam from the bagasse (as seen in S3 and S2). In the Group 1, S3 had the highest production of SuE, thus, S3 showed the lowest GWP. When considering the Group 2, S4 had the lowest total PLA production, thus S4 showed a lower GWP impact than that of S1 and S5 (S4<S1<S5). Figure 2a also shows the net GWP to be 402, 433, 458, 373, 430 t CO2 eq. for S1, S2, S3, S4, and S5, respectively. It can be seen that S4 has the lowest GWP among all five scenarios.

3.2 Energy resources

Figure 2b illustrates the energy resources results in each stage for all five scenarios. It can be seen that the ethanol conversion/PLA resin production stage consumed the highest amount of energy. In the feedstock processing stage, sugar milling generated surplus electricity and steam which could be used in other processes in the biorefinery. Therefore, scenarios S5, S4, and S1, which used more sugarcane (80% sugarcane) than the other scenarios (S2 and S3), could actually gain avoided energy (from surplus energy) as shown as negative values in Figure 2b. When comparing Group 1, S5 had the highest PLA production followed by S1 and S4, thus, S4 showed the lowest total energy resources due to the least amount of PLA production. The net energy resources impact are shown to be 4128, 4561, 4902, 3706, 4526 GJ LHV for S1, S2, S3, S4, and S5, respectively (Figure 2b).

From sections 3.1 and 3.2, we can see that S4 has the best environmental performance in both GWP and energy resources. However, S4 had the lowest revenue generated (Table 2) which made us question which scenario would be the best in both environmental and economic aspects. Thus, the Eco-efficiency parameter was developed in order to integrate the environmental and economic aspects together.

3.3 Eco-efficiency

Eco-efficiency is an indicator that is used to help businesses to be more effective efficient and responsible for natural resources and the environment. This indicator has been shown to be relevant to both economic and environmental aspects towards sustainable development. Eco-efficiency can be expressed as the ratio of economic creation to ecological destruction as shown in equation 1, thus the higher the Eco-efficiency parameter the better it is.

$$Eco-efficiency = \frac{Value\ of\ a\ product\ or\ service}{Environmen\ tal\ impact\ of\ a\ product\ or\ service} \tag{1}$$

In this study, two Eco-efficiency parameters were developed specifically to combine both environmental (GWP and energy resource impacts) and economic (revenue) aspects by using a ratio of normalized revenue and normalized environmental impacts. One parameter was for GWP impact (Eco-efficiency$_{GWP}$) and another was for energy resource impact (Eco-efficiency$_{Energy\ resources}$). The normalized values were calculated by dividing the revenue and environmental impact in each scenario with the average values obtained from all scenarios studied as shown in Figure 3a. These normalized values were used as benchmarks to aid in the fair comparison of all scenarios. The two Eco-efficiency parameters (Eco-efficiency$_{GWP}$ and Eco-efficiency$_{Energy\ resources}$), as calculated from normalized values, are shown in Table 4.

Table 4: Eco-efficiency$_{GWP}$ and Eco-efficiency$_{Energy\ resources}$ of scenarios in this study

Parameters	S1	S2	S3	S4	S5
Eco-efficiency$_{GWP}$	1.05	0.96	0.89	1.09	1.03
Eco-efficiency$_{Energy\ resources}$	1.07	0.95	0.87	1.14	1.02

Figure 3b illustrates the relationship between Eco-efficiency$_{GWP}$ and Eco-efficiency$_{Energy\ resources}$, which can be used to identify the best scenario. When being normalized, an Eco-efficiency value higher than 1 should be considered efficient in terms of both environmental and economic aspects. In addition, the higher the Eco-efficiency value (>1) the better the performance it is. Since two Eco-efficiency parameters (Eco-efficiency$_{GWP}$ and Eco-efficiency$_{Energy\ resources}$) have been developed in this study, the best scenario should have high values in both. Based on these criteria, S4 was shown to be the best scenario while S1 and S5 are also acceptable because their eco-efficiency values, in both GWP and energy resource impacts are higher than 1.

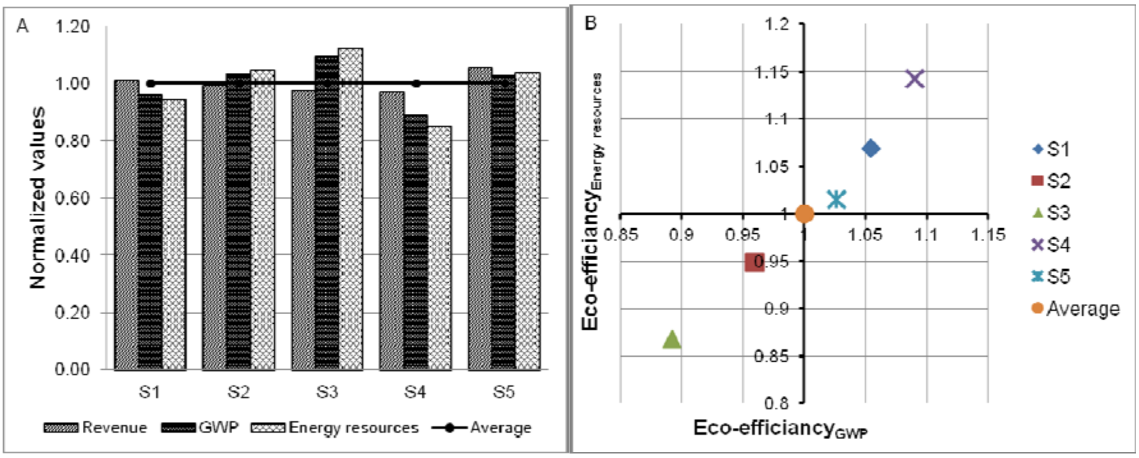

Figure 3: A) Normalized values for eco-efficiency parameter calculation, B) Relationship between Eco-efficiency$_{GWP}$ *and Eco-efficiency*$_{Energy\ resources}$.

4. Conclusion

In this study, a life cycle environmental impact assessment (LCIA) was performed in order to evaluate the performance of a biorefinery model in Thailand from both environmental and economic aspects by using five scenarios created by varying the ratio of raw materials (sugarcane and cassava) and the ratio of ethanol and PLA products produced. The environmental performance was evaluated in terms of GWP and energy resources used while revenue generated was used for the economic aspect. The results indicate that the model biorefinery would have better performance in both global warming potential (GWP) and energy resource impacts with increased sugarcane consumption. This could be due to the use of bagasse and biogas as sources of fuel to generate electricity and steam by using highly efficient electrical energy cogeneration process in the biorefinery. In contrast, increasing PLA production led to higher GWP and energy resource impacts because of higher electricity and steam consumption in the bioplastic production process. In order to identify the best scenario among the five scenarios studied, two Eco-efficiency parameters (Eco-efficiency$_{GWP}$ and Eco-efficiency$_{Energy\ resources}$) were developed in order to combine both environmental (GWP and energy resources) and economic (revenue) aspects by using normalized values based on average revenue gained and average impact associated. The results showed that S4 was the best scenario as it has the highest values in both Eco-efficiency parameters. This study showed that the environmental and economic of biorefinery performance could be improved by integrating efficient feedstock (Sugarcan and cassava) utilization and production of desired products (ethanol and PLA) with by-products utilization and waste minimization.

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