Towards Sustainable Production of Bioplastics

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Abstract

Polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) are promising bioplastics with bio-based and biodegradability properties. PLA and PHAs can potentially substitute conventional plastics such as polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS). This study aimed to evaluate sustainability of bioplastics production systems. Combined environmental and economic indicators, eco-efficiency (E/E), was selected to investigate the sustainability performance of PLA and PHAs in comparison with those of PP, PET and PS. The environmental impacts were determined using life cycle assessment (LCA). In this study, environmental impacts from "cradle-to-grave" of one-tonne plastic resin production with different disposal scenarios were investigated using the ReCiPe midpoint (H) method. The selected impact categories were global warming and fossil depletion potentials. E/E of PHAs with waste disposal system improvement was noted to be higher than those of PLA and conventional plastics, indicating more sustainability of the former. Increasing the recycling rate of conventional plastics reduced their environmental impacts and consequently improved the E/E. Since bioplastics cannot completely substitute their conventional counterparts, increasing the rate of recycling should be encouraged. To take advantage of the remarkable biodegradable and compostable properties of bioplastic, composting facilities should be simultaneously promoted.

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บทคัดย่อ

พอลิแลคติกแอซิด (PLA) และพอลิไฮดรอกซีอัลคาโนเอต (PHAs) เป็นพลาสติกชีวภาพที่ได้รับความสนใจเป็นอย่างมากจากสมบัติที่สามารถย่อยสลายได้ PLA และ PHAs สามารถนำมาใช้ทดแทนพลาสติกทั่วไปที่ผลิตได้จากปิโตรเลียม เช่น พอลิพอพิลีน (PP) พอลิเอทิลีน-เทเรฟทาเลต (PET) และพอลิสไตรีน (PS) งานวิจัยนี้มีวัตถุประสงค์เพื่อประเมินความยั่งยืนของระบบการผลิตพลาสติกชีวภาพด้วยดัชนีทางด้านสิ่งแวดล้อมและเศรษฐศาสตร์ หรือประสิทธิภาพเชิงนิเวศเศรษฐกิจ (E/E) เปรียบเทียบกับ PP PS และ PET โดยใช้การประเมินวัฏจักรชีวิตในรูปแบบ Cradle-to-grave เพื่อประเมินผลกระทบสิ่งแวดล้อม ได้แก่ ค่าศักยภาพในการทำให้เกิดภาวะโลกร้อน และการทำให้ทรัพยากรฟอสซิลลดลง ของการผลิตเม็ดพลาสติกปริมาณ 1 ตัน ด้วยวิธี ReCiPe midpoint (H) โดยกำหนดสถานการณ์การกำจัดขยะพลาสติกที่แตกต่างกัน ผลการศึกษาพบว่า E/E ของ PHAs ภายใต้การเพิ่มอัตราการกำจัดด้วยวิธีการหมักทำปุ๋ยมีค่าสูงกว่ากรณีของ PLA และพลาสติกทั่วไป หรือกล่าวได้ว่ามีความยั่งยืนกว่า ในการเพิ่มอัตราการรีไซเคิลพลาสติกทั่วไป พบว่าผลกระทบสิ่งแวดล้อมมีค่าลดลง ส่งผลให้ค่า E/E สูงขึ้น เนื่องจากการใช้พลาสติกชีวภาพเพื่อทดแทนพลาสติกทั่วไปไม่สามารถทำได้โดยสมบูรณ์ จึงควรสนับสนุนให้มีการรีไซเคิลพลาสติกทั่วไปมากยิ่งขึ้น อนึ่ง สมบัติที่โดดเด่นของพลาสติกชีวภาพคือสามารถย่อยสลายได้ การมีนโยบายผลักดันให้เกิดการผลิตและการบริโภคพลาสติกชีวภาพอย่างยั่งยืน จึงควรกระทำควบคู่ไปกับการสนับสนุนให้มีสถานที่กำจัดพลาสติกชีวภาพด้วยการนำมาผลิตเป็นปุ๋ยหมักด้วย

1. Introduction

Global production capacity of bioplastics has been continuously increasing and may reach 2.189 million tonnes in 2020 [1]. Polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) are promising bio-based and biodegradable bioplastics which can be made from renewable resources such as sugarcane, cassava, and corn, through fermentation process. With flexibility in their properties, PLA and PHAs can potentially substitute conventional plastics such as polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS). Due to the abundance of biomass feedstock, the Thai government launched its ambitious ten-year plan in 2017 to build a bio-economy hub for the region. Despite consuming less fossil resources, cultivation of agricultural crops for feedstocks can result in environmental impacts and may also give rise to issues pertaining to energy versus food.

Life Cycle Assessment (LCA) has been used as an effective tool to quantify environmental impacts associated with the entire life cycle of bioplastics. Many studies in the past [2–7] focused on 'cradle-to-factory gate'or from cultivation and harvesting of the feedstock to production of bioplastic resin. Meanwhile, some researchers paid attention on the impacts from acquisition of agricultural feedstock to disposal of bioplastic waste or 'cradle-to-grave' approach [6,8,9]. Even though it has been reported that bioplastics have carbon footprints lower than their conventional plastic counterpart, this may not necessarily lead to sustainability if their economic value is low.

Thus, considering environmental impacts alone may not be sufficient if the bioplastics need to be economically viable. Generally, an environmentally friendly product with a higher market price may not be successful to enter the market. Hence, economic impact should be a center of focus as well. Economic impacts of bioplastic production systems have been emphasized in many studies, especially on cost benefit analysis [10]. Nevertheless, these studies lack consideration of the entire life cycle of the bioplastics system or considered either environmental impacts or economic impacts, but not both. This study aims to evaluate the sustainability of bioplastics using the combination of environmental and economic indicators, eco-efficiency (E/E), to investigate the sustainability performance of PLA and PHAs from sugarcane and cassava in comparison with PP, PET, and PS.

2. Methods

2.1 Goal and scope of the study

The goal of this study is to compare the sustainability performance in terms of environmental and economic impacts of bioplastics to conventional plastics using E/E. The definition of E/E has been provided in Section 2.2. The midpoint impacts from cradle-to-grave life cycle assessment (LCA) of one tonne PLA and PHAs production from cassava and sugarcane and PP, PET, and PS are investigated. The intended audience of this study are policy makers. Hence, the results are useful to the bioplastic policy decision making process of the country.

2.2 Eco-efficiency

E/E has been defined as a key element for promoting fundamental changes in the way societies produce and consume resources. It is the ratio of product or service value to environmental impact [11]. The E/E can be expressed as in Eq. (1). In this study, the product system value (includes the market prices of PLA, PHAs [12], and conventional plastic resins [13] and waste management fees [14-15]) is used as the economic indicator. From the policy maker point of view, the product that creates higher value is the product of interest. Thus, in the calculation of the product system value, the waste management fee is subtracted from the market price of plastic resin. The prices and costs associated with the plastic system are presented in **Table 1.**

$$\text{Eco-efficiency} = \frac{\text{Product system value (THB)}}{\text{Total GHG emission (kg CO}_2\text{eq)}} \qquad (1)$$

Table 1 Prices and costs associated with the plastic systems

Item	Price/cost
PLA resin	93 THB/kg
PHAs resin	170 THB/kg
PP resin	47 THB/kg
PET resin	39 THB/kg
PS resin	56 THB/kg
Landfilling	0.9 THB/kg
Composting	0.8 THB/kg
Recycling	4.7 THB/kg

2.3 Life cycle assessment

Life cycle assessment (LCA) is a well-known environmental management tool to quantify environmental impacts associated with a product throughout its entire life cycle. The ReCiPe midpoint (H) method is used to investigate the midpoint impacts associated with the production and disposal of studied plastics. The selected impact categories are global warming potential (GWP) and fossil depletion potential (FDP). The system boundary of the bioplastics production includes feedstocks cultivation and harvesting, starch/sugar production, PLA/PHAs resin production, and disposal (landfilling and composting). Crude oil extraction and plastic resins production and disposal (landfilling and recycling) are included in the conventional plastics production system. System boundaries of bioplastic and conventional plastic resins production are illustrated in **Figure** 1 and **Figure 2**, respectively.

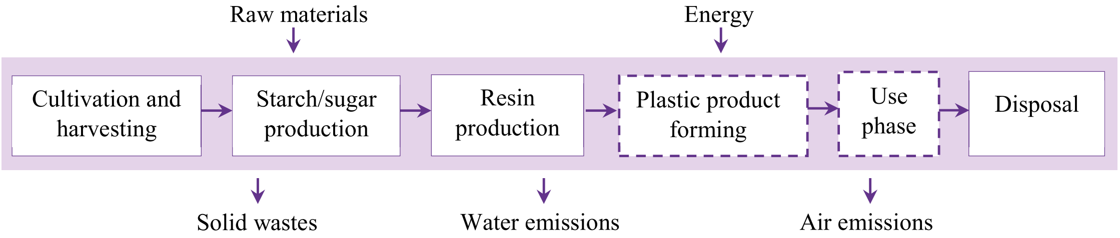

Figure 1 System boundary of bioplastic resins production

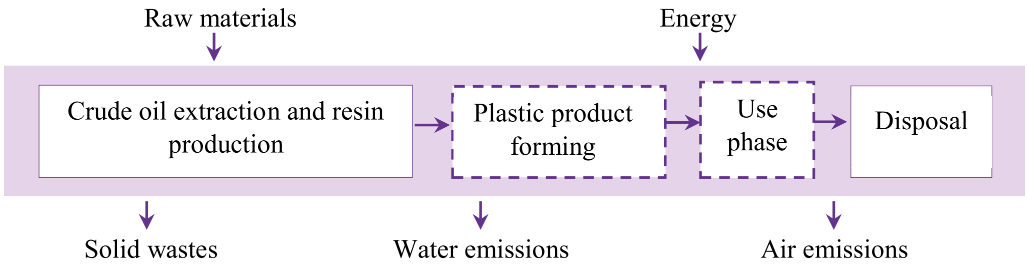

Figure 2 System boundary of conventional plastic resins production

The data on feedstock cultivation and harvesting and sugar/starch production are based on practices in Thailand. Life cycle inventories (LCI) of chemicals, materials, and fuels used are referred from the Thai national life cycle inventory database and ecoinvent 3 [16] database. Hence, the results are more specific to Thailand and may lead to limitation of the study results which may not be valid for other countries. Sources of data used in this study by each stage of the life cycle are as follow:

1) Feedstocks cultivation and harvesting and sugar/starch production

The Thai sugarcane farming data were from Pongpat et al. [17]. The average sugarcane yield is 67 tonne/ha-y. The input chemical fertilizers, pesticides, and fuels as well as emissions form the conventional practices are considered. At the sugar mill where sugarcane is converted to sugar, the data from Silalertruksa et al. [18] were used. Economic allocation is used to allocate environmental burdens among co-products; raw sugar, refined sugar, molasses ethanol, and surplus electricity from bagasse with allocation factors of 0.37, 0.50, 0.10, and 0.03, respectively. The data of cassava cultivation and harvesting were extracted from Kawasaki et al. [19]. Cassava starch processing data are from Jakrawatana et al. [20]. Environmental burdens are allocated between cassava starch and cassava pulp based on the economic values of the co-products. The allocation factors for cassava starch and cassava pulp are 0.94 and 0.06, respectively. The raw sugar and cassava starch used for bioplastic production are assumed to be the surplus from domestic consumption. Hence, the conversion of land to agricultural land area for sugarcane and cassava cultivation is not considered in this study.

2) Bioplastic resin production

PLA can be produced via fermentation process where sugar is converted to lactic acid before polymerization to PLA. The data on energy and chemicals used in the process are extracted from Groot and Boren [3]. PHAs is a linear polymer produced by bacterial fermentation of sugar. Data on PHAs production are from Khoo et al. [6]. Impacts from electricity consumption are adjusted using the Thai life cycle inventory database.

3) Disposal

In this study, disposal scenarios are made to investigate environmental impacts from improving waste disposal system. Currently, about 70% of community waste is disposed in sanitary landfills and about 30% of waste is recycled. Due to the biodegradability property of bioplastics, it would release methane under anaerobic condition of landfilling. Thus, it gives rise in global warming potential. With a proper composting facility, bioplastic can be converted to compost. A remarkable property of conventional plastic is recyclable, so, recycling of conventional plastics is considered in this study. The inventory data on disposal stage are from European reference life cycle database and ecoinvent 3. The data on landfill emission are retrieved from Chidambaram-padmavathy et al. [21]. The disposal scenarios are shown in **Table 2**.

Table 2 Disposal scenarios

Scenario	Type of plastic	Disposal (percentage)		
		Composting	Landfilling	Recycling
S1	Sugarcane-based PLA (sPLA)	30	70	-
S2	Sugarcane-based PLA (sPLA)	80	20	-
S3	Cassava-based PLA (cPLA)	30	70	-
S4	Cassava-based PLA (cPLA)	80	20	-
S5	Sugarcane-based PHAs (sPHAs)	30	70	-
S6	Sugarcane-based PHAs (sPHAs)	80	20	-
S7	Cassava-based PHAs (cPHAs)	30	70	-
S8	Cassava-based PHAs (cPHAs)	80	20	-
S9	PET	-	70	30
S10	PET	-	20	80
S11	PP	-	70	30
S12	PP	-	20	80
S13	PS	-	70	30
S14	PS	-	20	80

3. Results and Discussion

3.1 Life cycle environment impact

In the calculation of GWP, the CO_2 fixation through photosynthesis during cultivation of feedstocks is considered. The amount of 1,833.5 and 2,199.1 kg CO_2 per tonne PLA and PHAs resins, respectively are fixed. The majority of the municipal waste landfill facilities in Thailand are not equipped with gas recovery system, is referred in this study. The biogenic methane emission is taken into account. **Figure 3** shows the life cycle greenhouse gas emissions under different disposal scenarios. Bioplastics with current disposal scheme show higher GWP between the range of 4.72 x 10^3 to 1.64 x 10^4 kg CO_2eq per tonne resin while GWP of conventional plastics are in the range of 8.41 x 10^2 to 2.70 x 10^3 kg CO_2eq per tonne resin. The GWP of bioplastics production are mainly due to greenhouse gas emissions from landfilling and intensive electricity consumption in resin production process. The quantity of electricity required for the PLA and PHAs resin production process is 1.07 and 1.09 kWh/kg resin, respectively. From the calculation, it was found that the majority of the GWP during the disposal stage of bioplastics came from CH_4 emission from the landfill. When looking at the base case and disposal improvement, it can be clearly seen that GWP of the improvement cases are about 70 and 50 percent lower than the base case for bioplastics and conventional plastics, respectively. Comparison of the results with other studies [22-23] showed that the results of this study agreed well in terms of the resin production stage that exhibits higher GWP than the cultivation stage where CO_2 uptake from photosynthesis is taken into account. In addition, the GWP from landfilling of bioplastics waste showed higher value than the conventional plastics which is also consistent with the previous studies. However, GWP of the bioplastics are still higher than their conventional plastic counterpart. Comparison of different types of feedstock indicates that cassava-based bioplastics have higher GWP than sugarcane-based bioplastics. It is because of higher fermentation yields for sugarcane to bioplastics.

Despite lower GWP of conventional plastic, its FDP **(Figure 4)** is higher than bioplastics. This is due to the use of petroleum feedstock for conventional plastic resins production. By improving disposal system of bioplastics, the FDP is not remarkably reduced. In contrast, with improving disposal system of conventional plastics by increase recycling rate FDP are about 60 percent lower than the base cases. In bioplastic production system, FDP is mostly contributed from consumption of electricity derived from petroleum resources.

At the sugar mill, bagasse, molasses, and filter cake were utilized for electricity generation, bioethanol production, and fertilizer, respectively. Thus, the environmental burdens from the producing of sugar at the sugar mills are allocated between the co-products, thus reducing the burdens on the raw sugar used for the bioplastics production. Consequently, the GWP was relatively low. Likewise, the FDP was also contributed mainly by the resin production stage. This was due to the use of electricity.

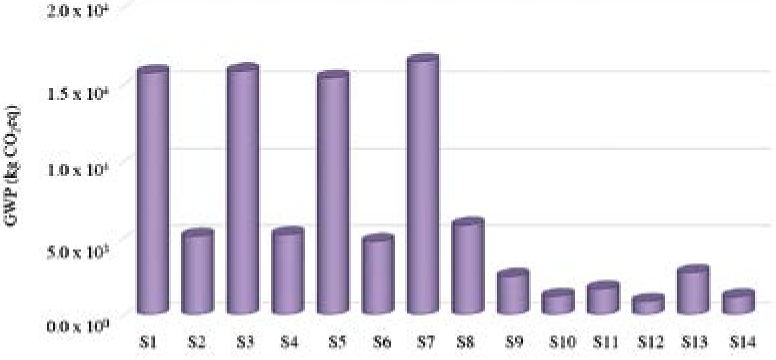

Figure 3 Global warming potential impact associated with the plastics life cycle

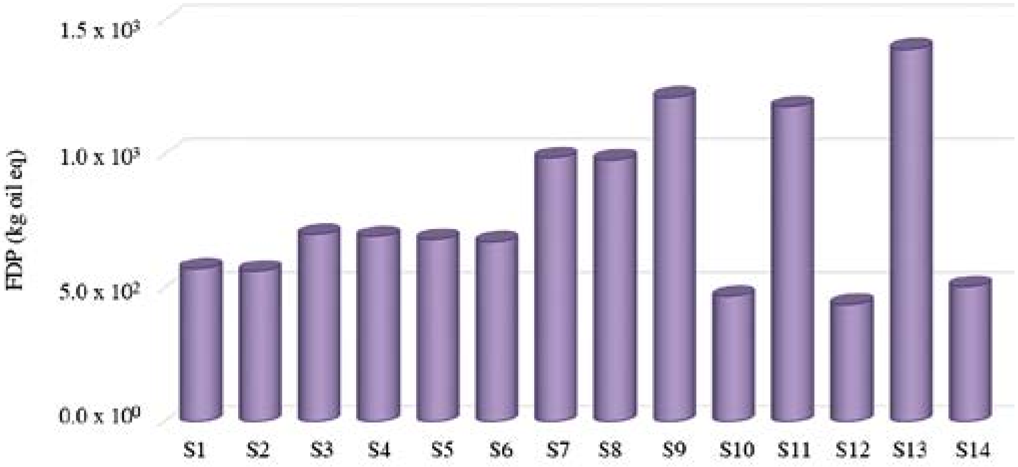

Figure 4 Fossil depletion potential impact associated with the plastics life cycle

3.2 Eco-efficiency assessment

It is difficult to point out whether bioplastics or conventional plastics are better. When looking at GWP, conventional plastics are better than bioplastics which is opposite to FDP. **Figure 5** shows E/E portfolio graph of bioplastics and conventional plastics. The environmental and economic indicators values are normalized in the range of 0.1-0.9. From the policy maker point of view, the product that creates higher economic value while exhibiting lower environmental impact is preferable. Due to the high market price of PHAs, E/E is higher than other plastics. Conventional plastics production technologies have been developed over a century. It makes mass conventional plastics production possible at low costs. However, the E/E of the disposal system improvement scenarios of all types of plastics are higher than their respective base cases. Based on the results of this study, PHAs should be promoted along with the appropriate composting facility. However, with a very high resin price, it is probably difficult to enter the market. It must be recognized that at present, the bioplastic production technology is in the beginning stage. With research and development in the field, mass production is expected to be achieved at a lower cost. Thus, eventually the bioplastic resin price is forecasted to be lower in the future when the market will mature. So for now, bioplastics could be promoted to be used for higher value products such as in medical applications for instance.

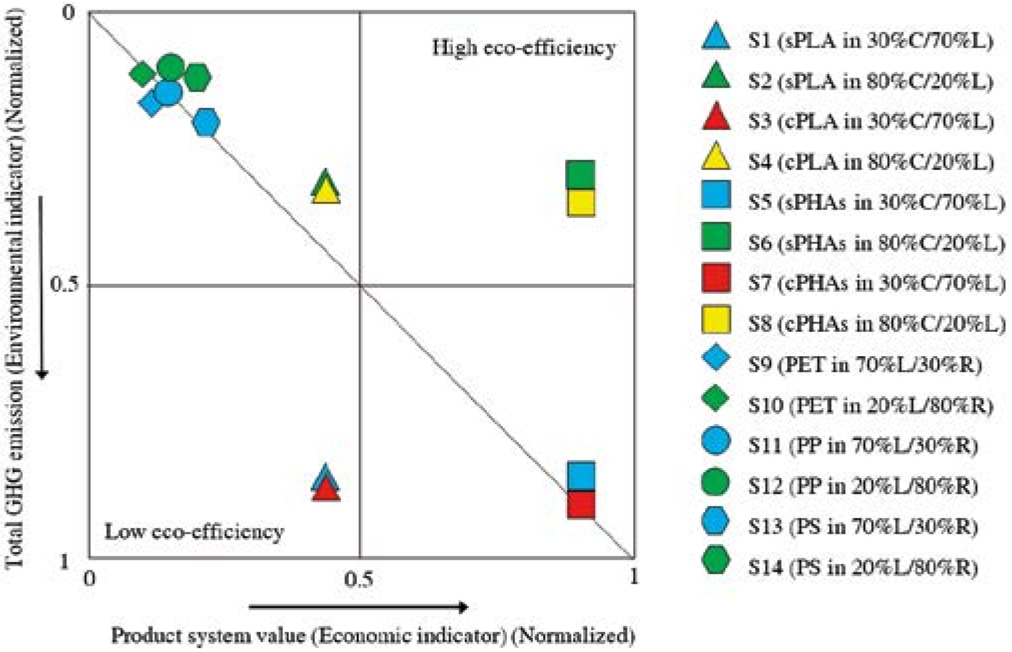

Figure 5 Eco-efficiency of bioplastics and conventional plastics

4. Conclusions

From the results, it can be seen that E/E of PHAs are higher than PLA and conventional plastics. E/E of PLA with the disposal system improvement are not much different from conventional plastics. With disposal system improvement, increasing rate of composting of bioplastics results in higher E/E. Similarly, by increasing recycling rate of conventional plastics, E/E show better values. Based on results of this study, recycling of conventional plastics should be promoted. However, contaminated or dirty plastics have not been recycled. They are mostly food packaging. Thus, bioplastics should be used for food packaging. Furthermore, bioplastic composting facility should be established.

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