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Environment impacts assessment of petroleum plastic and bioplastic carrier bags in Thailand

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Abstract: Due to the rapid increase in petroleum plastic consumption leading to severe waste problems and non-renewable resource depletion, bioplastics are an alternative option which can substitute petroleum plastic, serving as alternative renewable materials and expected to be more environmentally friendly. The goal of this study is to evaluate the environmental impacts in terms of global warming, fossil depletion, water depletion, land occupation, acidification, eutrophication, and toxicity for single-use carrier (shopping) bags produced from conventional plastic (HDPE) and bioplastic (PLA) and to find pros and cons of both products by applying the Life Cycle Assessment (LCA) tool. In addition, this study also focuses on the different waste management options. The results illustrate that petroleum plastic bags perform better than bioplastic bags in all categories and are quite similar in term of fossil depletion impact. The major stages contributing to the impacts of bioplastic bags are PLA production stage followed by the agricultural phase, particularly due to the higher resin requirement for bioplastic bag production as compared to plastic bags. Moreover, this study found that mechanical recycling is the most appropriate waste management option not just for petroleum plastic bags but also for bioplastic bags. However, there are other effects to the environment where bioplastics may be preferable to petroleum plastics, for instance, plastic waste accumulated in the deep marine environment and turning into microplastics affecting on the marine species, as well as persisting in the landfill for decades or centuries. Currently, the LCA study does not cover these impacts which are thus not mentioned in the study but will be beneficial to study further in the future.

***Keywords*:** Life cycle assessment (LCA), Polylactic acid (PLA), High-density polyethylene (HDPE), Single use carrier bags, Sugarcane.

1. Introduction

The global plastics production increased drastically during 1950 to 2014 from 15 to 311 million metric tonnes, or more than 20 times in just about 65 years [1]. Because plastics are cheap, with high strength and durability, and have many applications, a large quantity of plastics are produced and their waste discharged to the river, ocean, and other ecosystems causing adverse environmental impacts [2]. Moreover, the conventional plastics are mostly produced from limited nonrenewable resources such as crude oil, natural gas, and coal [3]. Globally, more attention is recently being paid to bioplastics due to their favourable properties such as the use of renewable resources and biodegradation property to alleviate the disposal problem and toxic accumulation to the environment [4]. Bioplastics or bio-based plastics can be produced from agricultural feedstocks such as sugarcane, corn, and cassava. Examples of some common bio-based plastics are polylactic acid (PLA), polyhydroxyalkanoate (PHA), and polybutylene succinate (PBS) which can replace polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP). As Thailand has a flourishing agriculture sector, it is an opportunity for bioplastics which are produced from agricultural feedstocks to penetrate the plastics market. One of the very promising feedstocks to produce bioplastic is sugarcane as it is an industrial field crop in Thailand which is the 2nd largest sugar exporter after Brazil [5]. Presently, one of the major types of bioplastics produced in the market is PLA and Thailand has a potential to be a bioplastics hub [6].

In Thailand, plastics are used in almost every sector, for example, packaging, furniture, transportation, construction, electrical and electronic applicances, and warehouses. According to the statistics of plastic production in Thailand, the highest proportion of plastic used is in the production of packaging. In 2015, there were 2.048 million tonnes of plastic produced for plastic packaging with about 0.476 million tonnes for plastic single-use carrier (shopping) bags, 0.09 million tonnes for food trays, and 1.482 million tonnes for other packaging (box, cup, etc.) [7].

Life cycle assessment is a beneficial tool for assessing environmental impacts associated with a material, product, process or service all over the life cycle that is cradle to gate or cradle to grave [8]. The results may vary depending on scope, system boundary, geography and time. Several LCA studies about bioplastics in the past have shown their advantage as compared to conventional plastics particularly in the environmental impacts of global warming and fossil depletion [9-11]. Moreover, many studies have also argued that bioplastics have a negative effect on the environment such as land use change [12] due to land expansion and land required for feedstock cultivation for bioplastic; ozone depletion, eutrophication, acidification impact due to the fertilization. [13-15]. There is still a lack of studies focusing on water depletion, land occupation, and toxicity. In addition, some studies investigated only the comparison of the end of life options of bioplastics [15-16]. Therefore, the other environmental impacts of bioplastics in addition to greenhouse gas emissions and fossil use should also be emphasized in order to have an overall perspective and to find out more strengths and weaknesses of using bioplastics. A full life cycle assessment (LCA) would serve as an appropriate tool for such an evaluation. This study focuses on the evaluation and analysis the environmental impacts from cradle to grave of sugarcane-based and petroleum-based plastics by using carrier bags as the representative product based on a life cycle approach.

2. Materials and Method

Life cycle assessment (LCA) was applied as a tool in this study following ISO 14040 framework [8] and ISO 14044-guidelines and requirements [17]. LCA is a tool to evaluate the environmental aspects of the products or services over their entire life starting from the raw materials from which they are made until the final disposal. Life cycle assessment comprises four main stages which are goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation.

2.1 Goal and scope definition

The aim of this study is to evaluate the environmental impacts in terms of global warming, fossil depletion, acidification, eutrophication, land occupation, water depletion, and toxicity for whole life cycle of petroleum plastic (HDPE) and bioplastic (PLA) single-use carrier bags. Moreover, the study also considers the environmental impacts for the different end of life options in order to address the appropriate waste management for these bags. Waste management options include landfill, incineration, recycling, and composting. Composting option will be considered only for bioplastic bags. The customer use phase is excluded from this study as it is anticipated to be quite similar for both bioplastic and plastic single-use carrier bags. The reuse of both types of carrier bags is also not included in the study as the consumer behavior for the second use of both bags is quite subjective, but is assumed to be the same for both types of bags and will thus not affect the comparative results. The representative of petroleum plastic bag and bioplastic bag in this study are high-density polyethylene (HDPE) and polylactic acid (PLA), respectively.

The scope of bioplastic bag includes sugarcane cultivation and harvesting, sugar milling, PLA resin production, and bioplastic bag production. While petroleum plastic bag starts with crude oil production, naphtha production, ethylene production, HDPE resin production, and plastic bag production. Furthermore, the study also focuses on the different disposal options for bioplastic and plastic bags, landfill, composting, mechanical recycling,and incineration. The life cycles of bioplastic and petroleum plastic bags are shown in Figures 1 and 2, respectively. The functional unit (FU) of this study is focused on the plastic single use carrier bags produced and distributed in Thailand in one year, viz. 125,000 tonnes of plastic single-use carrier bags [18] which is equal to 14,300 million bags.

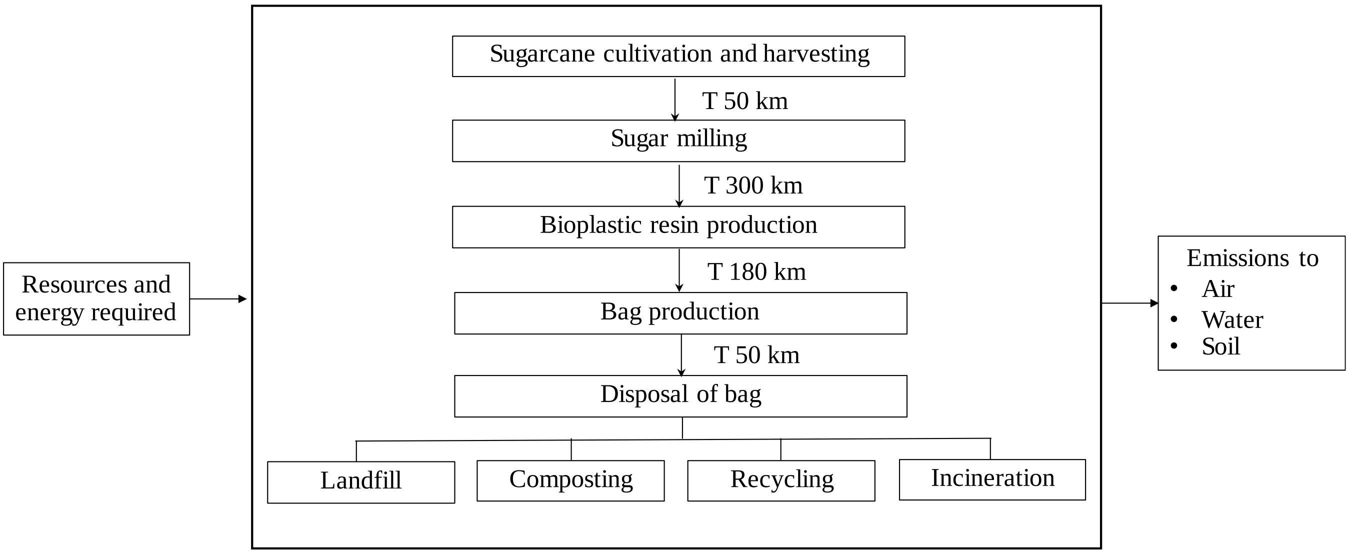


Figure 1. System boundary of bioplastic bag.

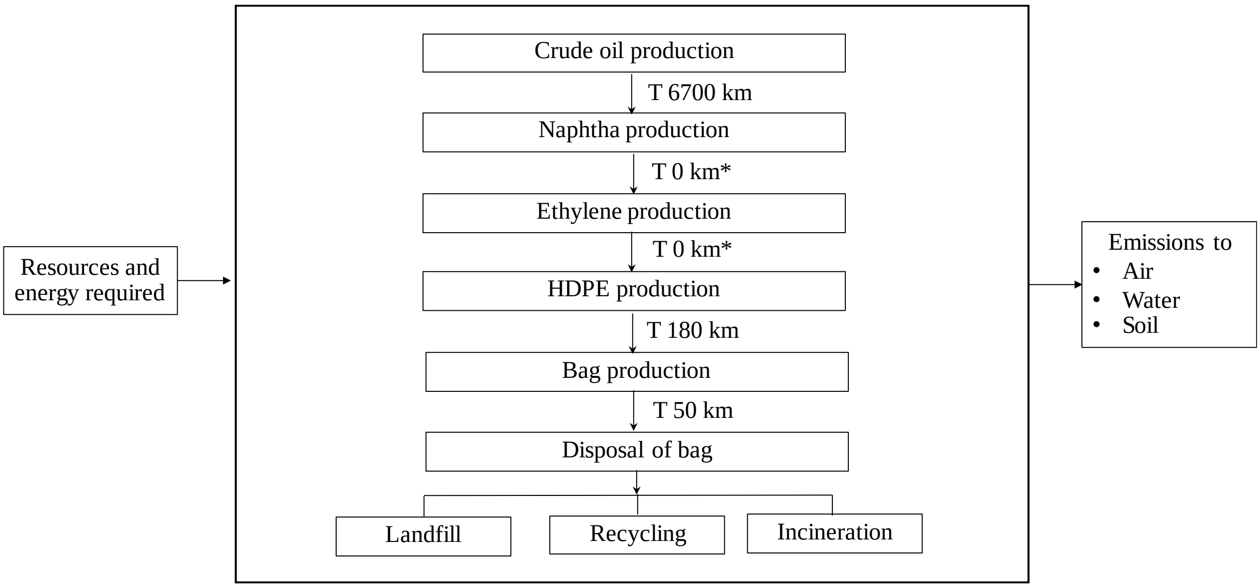


Figure 2. System boundary of plastic bags (* Remark: T represents transportation. The transportation distance of naphtha, ethylene, and HDPE was zero due to their plant are located in the same area.).

Table 1. Characteristics of bags.

Characteristics	Dimensions of a standard bag			Density (g/cm^3)	Weight of bag (g)
	Length (cm)	Width (cm)	Thickness (mm)		
Plastic bag	30.48	50.8	0.06	0.94	8.74
Bioplastic bag	30.48	50.8	0.06	1.25	15.48

2.2 Life cycle inventory analysis

The inventory data were compiled from the research work and databases available in Thailand as much as possible. As the bioplastics production is in initial stage, therefore some data are gathered from international publications. The detail of each production stage is described in the following section.

2.2.1 Characteristics of bags

The dimensions of a standard bag and density of plastic bag and bioplastic bag are shown in Table 1. To make these two different types of bag comparable, this study assumed that bioplastic and plastic bags have the same carrying capacity of 20 kg. Therefore, the density and weight of plastic bag are 9.41×10^2 kg/m^3, 8.74g and of bioplastic bag are 1.25×10^3 kg/m^3, 15.48g, respectively. The calculation is referenced from the relevant literature [19].

2.2.2 High-density polyethylene (HDPE) production

The HDPE production includes crude oil extraction, naphtha production, ethylene production, and HDPE resin production. Crude oil is a raw material to produce naphtha, coming from petroleum refineries. Then naphtha processed to ethylene by steam cracking. Ethylene polymerizes to form the resin of HDPE. The background data of crude oil production, extraction and naphtha were gathered from ecoinvent 3 and Chiarakorn et al. (2016) [20]. The inventory of both ethylene and HDPE production were derived from the Thai national LCI database [21].

2.2.3 Sugarcane cultivation and harvesting

Sugarcane cultivation and harvesting include land preparation, plantation, cultivation, and harvesting. The inventory data were obtained from the study by Pongpat et al. (2017) which using the questionnaire and interview to sugarcane growers and laborers in the Central region of Thailand [22]. According to the field survey, the most preferred harvesting technique is semi-mechanized burnt cane harvesting. Data for the PLA pellet manufacturing in this study were retrieved from Groot and Boren (2010) [23]; the factories studied are located in Central Thailand and supply Bonsucro certified sugarcane.

2.2.4 Sugar milling

The data in this stage were extracted from the study by Silalertruksa et al. (2017) [24]. Sugarcane is sent from field to the sugar mill in order to extract the sugarcane juice. Then sugarcane juice is passed through the clarification and evaporation process to get the syrup. This syrup is then added to vacuum pan in order to get the sugar crystals and molasses. Finally, the sugar crystals are separated from the molasses by the centrifugation process. These sugar crystals are called raw sugar which is the main product from sugar milling. There are also co-products viz. refined sugar, molasses, and bagasse. The environmental burdens are shared between the main product and co-products based on the economic allocation. The allocation factors for raw sugar, refined sugar, molasses, and excess bagasse are 0.37, 0.50, 0.1 and 0.03, respectively [24]. Raw sugar will be further used as a raw material to produce PLA.

2.2.5 PLA production

Polylactic acid is produced from lactic acid which is derived from the fermentation of sugar. Electricity, steam, lime, sulfuric acid, and potassium hydroxide are needed in this stage to produce lactic acid. The production of polylactic acid has two main processes which are direct condensation polymerization of lactic acid and ring opening polymerization. The inventory data for this stage are retrieved from Groot and Boren (2010) [23].

2.2.6 Bags production

To produce 1 kg of bioplastic bags, the energy required is 1.045 kWh/kg bioplastic bag. Whilst, to produce 1 kg of a plastic bags, the energy required is 0.758 kWh/kg HDPE bag. It was assumed that during resin production there is no loss [25]. Therefore, 1 kg of resin is converted to 1 kg of bags.

2.2.7 Disposal options for both types of carrier bags

(1) Landfill

Life cycle inventory on this disposal option is retrieved from the study by Leejarkpai et al. (2016) which was carried out under the real landfill conditions in Thailand [26]. The chemical formula of PLA is $C_3H_4O_2$. Under landfill condition, after 4 months some PLA sheets start to break down into a small fraction and within 16 months, the degradation of PLA is complete. To evaluate the amount of landfill gas generation from PLA in the landfill, the theoretical stoichiometry for the anaerobic reaction is estimated by using equation (1).

$$\text{PLA: } C_3H_4O_2 + 1.0\ H_2O \rightarrow 1.5\ CH_4 + 1.5\ CO_2 \qquad (1)$$

Petroleum plastic cannot be degraded under real landfill conditions. Thus, it was assumed that there are no GHG emissions from landfilling of petroleum plastic. However, there are some GHG emissions from the activities at the landfill including compaction and loading waste process which require 10.6 kWh electricity per tonne waste [19].

(2) Composting

Composting option is considered only for bioplastic bags as only these can be degraded under appropriate conditions. Under aerobic composting system, the aerobes produce the enzyme to break down the polymer. The reaction for this activity is shown in the equation (2) [27].

$$\text{PLA: } C_3H_4O_2 + 3.0\ O_2 \rightarrow 3.0\ CO_2 + 2.0\ H_2O \qquad (2)$$

The inventory of composting was extracted from the study of Andrade et al. (2016) and includes the energy use for sorting, grinding, and placing of compostable waste including PLA in the window [16].

(3) Recycling

Mechanical recycling was selected for consideration in this study. In the recycling process, not all recyclable materials cannot be fully recovered. They might have lower properties and loss during reprocessing. Hence, only 81% can substitute virgin HDPE product. On the other hand, about 96% of PLA can be recovered via recycling. The data were retrieved from De Andrade et al. (2016) [16] and Rigamonti et al. (2014) [28].

(4) Incineration

In this study, it was assumed that the efficiency of incineration system to produce electricity is about 17.8% based on the dedicated incineration facility technology used for plastics in the US [29]. The lower heating value (LHV) of polymers are used to estimate the electricity production. The lower heating values of PLA and HDPE are 17.9 MJ/kg and 46.53 MJ/kg, respectively. The emissions from the incineration process were extracted from McDougall et al. (1994) [30]. It was supposed that the energy gained from incineration of HDPE and PLA waste will displace an equivalent amount of the Thai grid mix electricity. The data sources for each life cycle stages are compiled in Table 2.

Table 2. The data source for life cycle of plastic bag production and its end of life options.

Stage	Data source
Sugarcane cultivation and harvesting	[22]
Sugar milling	[24]
PLA resin production	[23]
Bag production	[25]
Crude oil production	Ecoinvent 3 database
Naphtha production	[20]
Ethylene production	[21]
HDPE resin production	[21]
Landfill	[19, 26]
Composting	[16]
Recycling	[16, 28]
Incineration	[29-30]
Chemicals	Ecoinvent 3 database
Electricity	[21]
Transportation	[21]and Ecoinvent 3 database

2.2.8 Transportation

The transportation assumptions for both types of bags is described as follows. Sugarcane is transported 50 km from field to sugar mill (in the Central region) by 10-wheel, 16-tonne truck. The distance from sugar mill to bioplastic resin producer (at Rayong) is 300 km by 10-wheel, 16-tonne truck. Besides, the crude oil is shipped from the Middle East to the petroleum refinery plant at Rayong about 6,700 km by ocean tanker. Crude oil is refined to naphtha and cracked to ethylene at the refinery. The petroleum refinery, monomer, and polymer plant of petroleum-based are located at the same area in Rayong. HDPE and PLA resin is transported from the plant to the bag producer about 180 km by 10-wheel, 16-tonne truck. The transportation of finished goods to customer was not considered in this study. Finally, both plastic and bioplastic bags after use are sent to disposal facilities about 50 km away by 10-wheel waste dump type truck.

2.2.9 The potential of sugarcane for bioplastic production in Thailand

Thailand is the world's second largest exporter of sugar after Brazil [31]. The Thai government has encouraged the zoning policy by transforming the abandoned paddy fields to sugarcane, cassava, and palm oil plantations. Sugarcane is considered especially appropriate for that purpose because all parts of it can be utilized as value-added products for other industries. Apart from sugarcane being utilized for sugar production, its co-products, molasses and bagasse, are further used as a raw material for ethanol production and bio-electricity or particle board, respectively [5]. The sugarcane plantation area and yield are approximately 1.4 Mha and 74 t/ha, respectively [31].

Furthermore, the Thai government also promoted the alternative energy produced from agriculture feedstocks for example; biogas, bio-diesel, and bio-ethanol in order to reduce import of fossil fuels and greenhouse gas emissions. Bio-ethanol can be produced from sugarcane, cassava, and cane molasses [32].

In addition, sugarcane can be used to produce bioplastics. The Office of Cane and Sugar Board (OCSB) has announced a plan to restructure the sugarcane industry by enhancing the productivity of sugar and to further produce other products (e.g. bioplastic and ethanol from cane).

2.3 Impact assessment

This step converts the life cycle inventory to environmental impacts. The ReCiPe midpoint method (version 1.13, 2016) was selected in this study. The environmental impact categories which considered are the impacts of global warming, fossil depletion, acidification, eutrophication, land occupation, water depletion, and toxicity .

3. Results and Discussion

3.1 Lifecycle impact assessment results: Cradle to gate

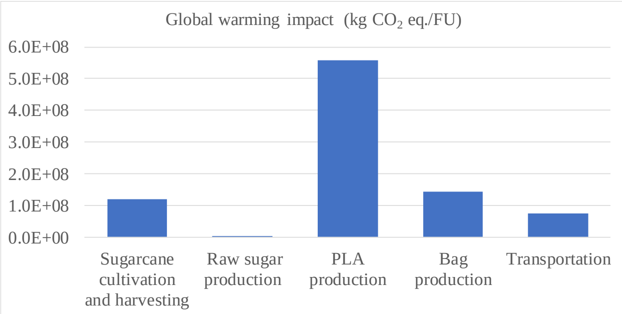
The environmental impact results of the carrier bags from cradle to gate are displayed in Figures 3-9. The details of each impacts are discussed below.

Global warming

The life cycle of global warming impact from the raw material acquisition to the production of bag for the bioplastic and plastic bags were 9.01×10^8 kg CO_2 eq./FU and 4.05×10^8 kg CO_2 eq./FU, respectively. The major contributor of global warming impact for bioplastic bag was PLA resin production (67%), especially from the utilization of chemicals and energy. The second largest contributor was sugarcane cultivation and harvesting (14%) due to the production and utilization of nitrogen fertilizers. Meanwhile, the main contributor to global warming impact of HDPE was ethylene production (monomer), accounting for 37%. It was seen that producing PLA and HDPE bags required different amounts of resin; the amount required for the production of each bag being 15.48 g and 8.74 g of PLA and HDPE resin, respectively. As the bioplastic consumed more material, it led to release more greenhouse gases. On the other hand, the global warming impact during blow film extrusion for bag production of HDPE bag was higher than PLA bag but the result revealed that the total global warming impact of the PLA bag was higher than the HDPE bag. The result, displayed in Figure 3, is in line with the studies by Khoo et al. (2010) and Kaewphan and Gheewala (2013) [19, 33]. The reason that made our study results different from other studies was the amount of resin used in the production of products. In other studies, an equal amount of resin were used to produce bioplastics and petroleum products [3, 11]. In this study on the hand, the amount of resin to produce bioplastic products were almost twice that of comparable products from conventional plastics based on functional equivalence (rather than equal weight of resin). Furthermore, the study by Suwanmanee et al. (2010) [9], Gironi and Piemonte (2010), and Taengwathananukool et al. (2013) [11], took CO_2 uptake during plant growth into account but did not take release into account as they considered cradle-to-gate (thus not including end-of-life where the carbon in the bioplastic would ultimately be released as CO_2). Whilst, this study did not take CO_2 absorption into account because CO_2 was released as CO_2 biogenic emission at the end of life and thus balances the initial CO_2 uptake during photosynthesis. This made the global warming impact of bioplastics products in this study higher than petroleum-based ones.

Fossil depletion

The production of PLA bags contributed 2.49×10^8 kg oil eq./FU while HDPE bags contributes 2.89×10^8 kg oil eq./FU. The results of fossil depletion impact exhibited that the PLA bags consumed less fossil resources than the HDPE bags. The major contributor to the fossil depletion impact of PLA bags was PLA resin production due to the electricity consumption in the production process, accounting for over 70% of the total. On the other hand, the biggest contributor for HDPE bags was crude oil extraction and production with about 44% of the total. The result of this study confirms one of the anticipated benefits of bioplastics and is also consistent with the studies by Gironi and Piemonte (2010) [10] and Groot and Boren (2010) [23] which concluded that bioplastics can save fossil resources. The results of this impact category are shown in the Figure 4.



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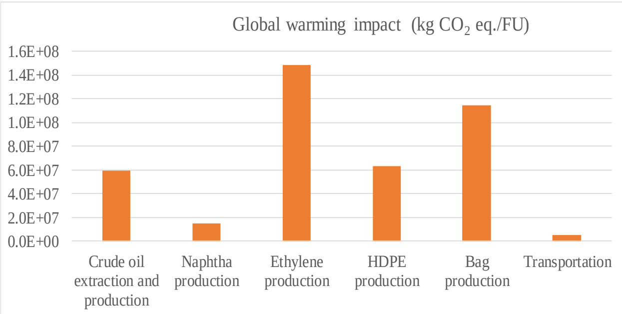

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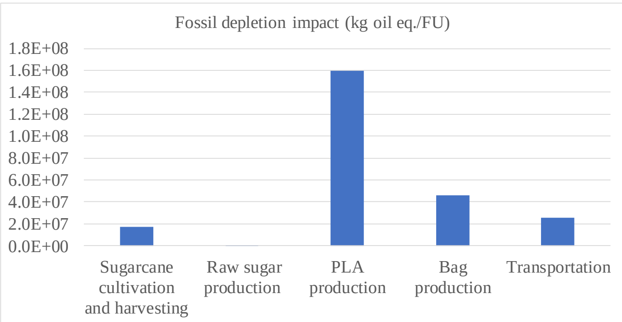
Figure 3. (a) Global warming impact of bioplastic (PLA) bags production per functional unit (14,300 million bags); (b) Global warming impact of petroleum plastic (HDPE) bags production per functional unit (14,300 million bags).



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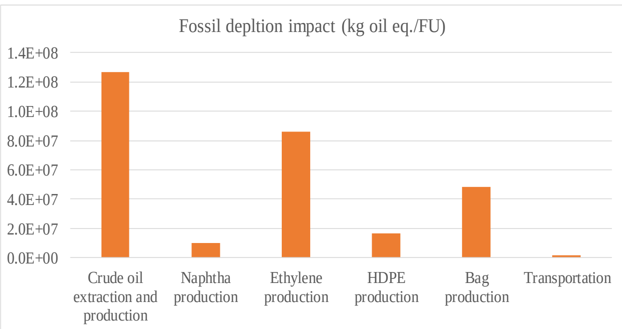
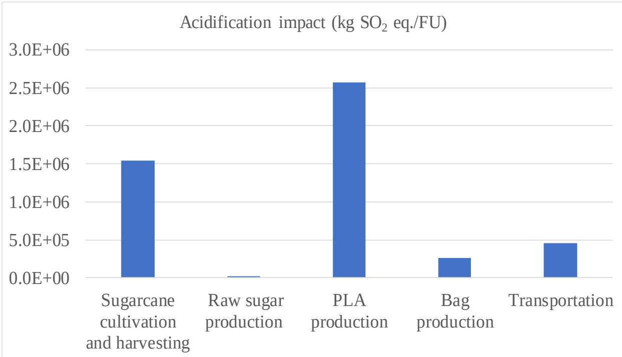


(b)

Figure 4. (a) Fossil depletion impact of bioplastic (PLA) bags production per functional unit (14,300 million bags); (b) Fossil depletion impact of petroleum plastic (HDPE) bags production per functional unit (14,300 million bags).

Acidification

The acidification impact of bioplastic (PLA) bags production was 4.84×10^6 kg SO_2 eq./FU. The main contributor was the utilization of sulfuric acid in the polylactic acid production process (53%) which was caused by emission of SO_2, followed by the fertilization and emissions from the application of fertilizers during sugarcane cultivation and harvesting (45%). Meanwhile, HDPE bag contributed 2.06×10^6 kg SO_2 eq./FU which was mostly from ethylene production (39%) followed by crude oil extraction and production (33%) as shown in the Figure 5. The comparison between PLA and HDPE bag showed that sugarcane-based PLA bags had higher acidification impact than HDPE bags which is consistent with the results of the study by Khoo et al. (2010) [19]. They are mainly following the same pattern as global warming impact and thus lead to a similar discussion.



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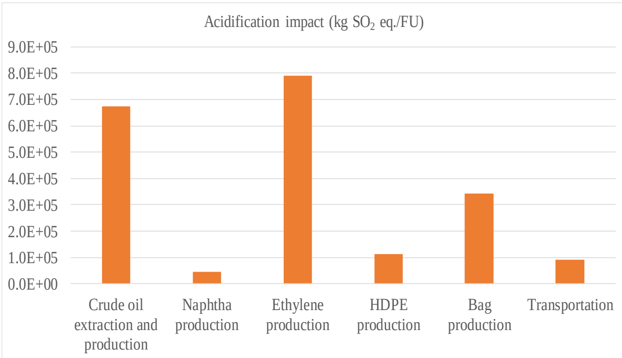


(b)

Figure 5. (a) Acidification impact of bioplastic (PLA) bags production per functional unit (14,300 million bags); (b) Acidification impact of petroleum plastic (HDPE) bags production per functional unit (14,300 million bags)

Eutrophication

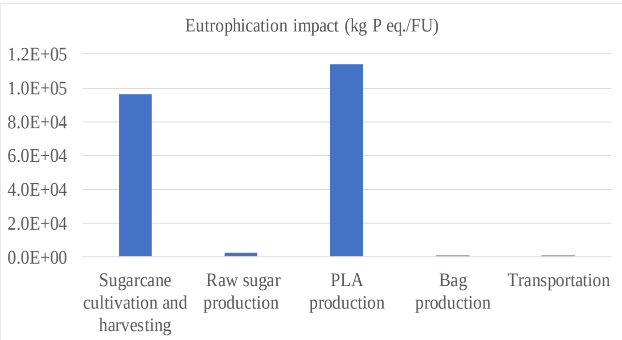
The eutrophication values of PLA and HDPE bags were 2.13×10^5 kg P eq. per FU and 2.32×10^4 kg P eq. per FU, respectively. The stage of PLA that contributed the most to eutrophication impact was PLA resin production (53%) followed closely by sugarcane cultivation and harvesting (45%). On the other hand, the major stage of HDPE bag contributing to eutrophication impact was monomer production (ethylene) accounting for 47% of the total. The eutrophication impact of bioplastic bags is higher than their petroleum plastic bag counterparts. The results of this study, illustrated in the Figure 6, are in agreement with the study by Gironi and Piemonte (2010) and Maldival (2009) [10, 13]. The reason that makes bioplastic bags contribute higher eutrophication impact than petroleum plastic bags is because the former are produced from biomass feedstock; the nutrients from the fertilizers applied during cultivation can reach the water bodies. In addition, the process of producing chemicals used in the production of bioplastics also releases eutrophying substances.

Water depletion

Water depletion impact of PLA and HDPE bags were 1.35×10^7 m^3/FU and 1.48×10^6 m^3/FU, respectively, as shown in the Figure 7. As could be anticipated, the results showed that PLA bags had a higher impact than HDPE bags; this is because sugarcane cultivation for the production of bioplastic bags required a large amount of water for agricultural activities (contributing 57%). Therefore, to alleviate the impact of water use on the cultivation of feedstock for bioplastic bag production in the future, it is important to prioritize and support water resource management in order to avoid water shortage and not compete with the water used in other agricultural sectors.

Toxicity

The toxicity impact results of bioplastic bag and petroleum plastic bag were 1.66×10^8 kg 1,4-DB eq/FU and 5.00×10^7 kg 1,4-DB eq/FU, respectively as shown in the Figure 8. The major stage that contributed the most toxicity impact for bioplastic bag was PLA resin production stage which was about 82% of the total due to the use of high chemical use, especially the process of producing sulfuric acid to supply in the production of PLA. This was followed by the use of fertilizer, especially the utilization of nitrogen fertilizer and pesticide during cultivation and crop protection. In contrast, for petroleum plastic bag the major contribution to this impact was from crude oil extraction and production which was about 44% of the total followed by monomer production (ethylene) and HDPE bag production which accounted for 32% and 17% of the total, respectively.



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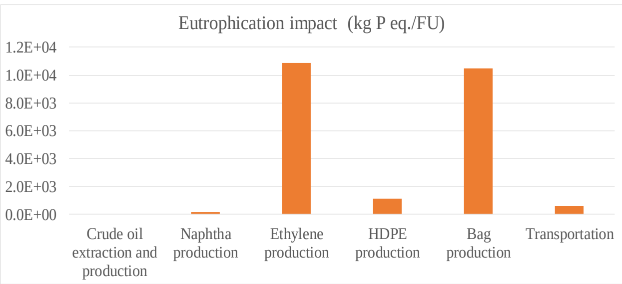

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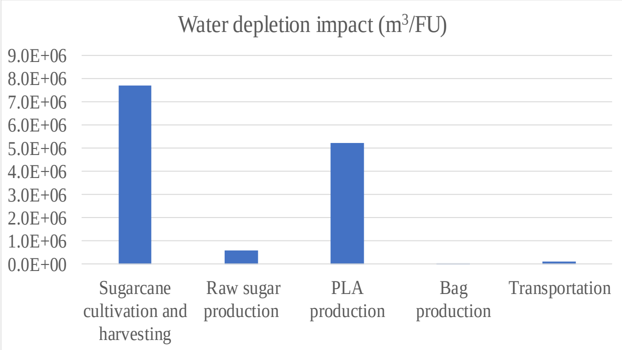
Figure 6. (a) Eutrophication impact of bioplastic (PLA) bags production per functional unit (14,300 million bags); (b) Eutrophication impact impact of petroleum plastic (HDPE) bags production per functional unit (14,300 million bags).



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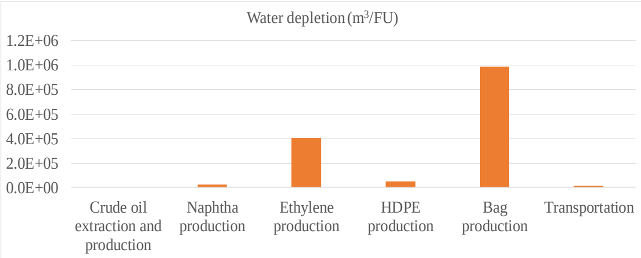

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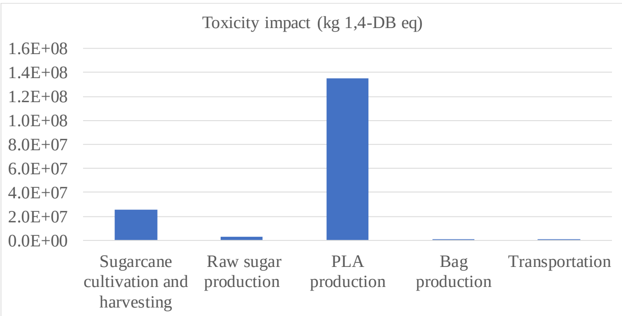
Figure 7. (a) Water depletion impact of bioplastic (PLA) bags production per functional unit (14,300 million bags); (b) Water depletion impact impact of petroleum plastic (HDPE) bags production per functional unit (14,300 million bags).



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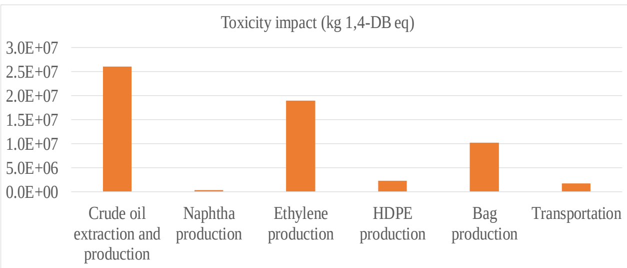
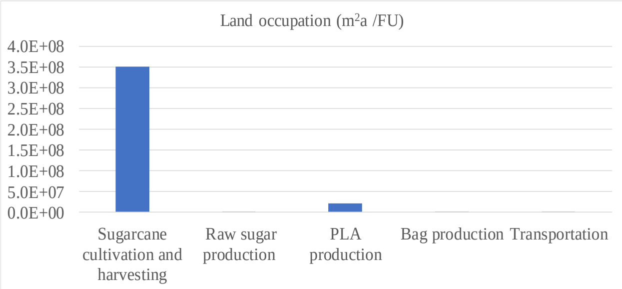


(b)

Figure 8. (a) Toxicity impact of bioplastic (PLA) bags production per functional unit (14,300 million bags); (b) Toxicity impact impact impact of petroleum plastic (HDPE) bags production per functional unit (14,300 million bags).

Land occupation

The last impact categories considered was land occupation. Land occupation values of PLA and HDPE bags were 3.73×10^8 m^2a/FU and 7.12×10^6 m^2a/FU, respectively.The much higher land occupation value of PLA bag is because the cultivation of crops for feedstock production requires agricultural land which contributed about 94% of the life cycle impact of the bioplastic bags. The results of land occupation impact are shown in the Figure 9.



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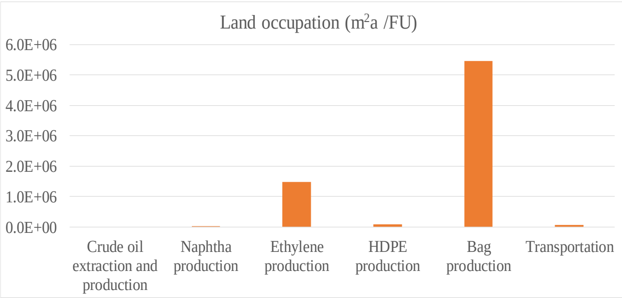

(b)

Figure 9. (a) Land occupation of bioplastic (PLA) bags production per functional unit (14,300 million bags); (b) Land occupation of petroleum plastic (HDPE) bags production per functional unit (14,300 million bags).

3.2 Cradle to grave with disposal options

The disposal technologies applied for the end-of-life in this study include landfill (with energy recovery), composting, incineration, and mechanical recycling. In this section, only global warming and fossil depletion impacts were considered in order to highlight the appropriate waste management for bioplastics.

Cradle to grave with landfill option

In this study, for HDPE bags in a landfill, it was assumed that there was no degradation of plastic waste which was consistent with the study by Bohlmann (2004), Mardival et al. (2009), Gironi and Piemonte (2010), and USEPA (2015) [10, 13, 29, 34]. Thus, the activity that contributed to the global warming was only the use of energy during landfilling activities such as loading and compaction. It contributed 1.11×10^6 kg CO_2 eq./ FU to the global warming from cradle to grave (Figure 10). On the other hand, the landfill treatment option for bioplastic bag was considered with the energy recovery. Bioplastic was assumed to degrade under the anaerobic condition which emits CO_2, CH_4, and water [26]. It was found that the global warming impact of bioplastic bags treated via landfill was 4.02×10^6 kg CO_2 eq./FU. For the recovery at landfill, methane was collected to produce electricity. Only 60% of the methane released from the landfill was assumed to be captured with the rest being released to the atmosphere as fugitive emissions. 1 m^3 of methane can generate about 3 kWh; this can in turn save 1.28 $\times10^5$ kg CO_2 eq./ FU with the total benefit of 2.07×10^5 kWh of electricity which can substitute an equal amount of grid electricity leading to the GHG benefits. Therefore, the net global warming impact was 3.89×10^6 kg CO_2 eq./FU. But if considering for the whole life cycle of bioplastic and plastic bag from cradle to grave with landfill treatment, the global warming impacts were 8.37×10^8 kg CO_2 eq./ FU and 3.32×10^8 kg CO_2 eq./ FU, respectively. The higher impact of bioplastic bag came from its degradation in the landfill. Moreover, the fossil depletion impact for the entire life cycle of bioplastic and petroleum bags are quite similar at 2.26×10^8 kg oil eq./FU and 2.30×10^8 kg oil eq./FU, respectively.

Cradle to grave with composting option

PLA waste can be degraded under aerobic conditions and turned to a high nutrient organic compound. The emission during the composting process was CO_2 which, being considered as biogenic carbon, did not contribute to global warming impact. The global warming impact of PLA bags for the whole life cycle with composting option was 8.28×10^8 kg CO_2 eq per FU. This study does not account for the benefit of compost product even though it can be used as a soil amendment or substitute for the organic fertilizer and peat because it was insignificant. The composting option did not show any benefit in term of fossil depletion.

Cradle to grave with mechanical recycling option

The data for mechanical recycling were retrieved from Andrade et al. (2016) where PLA waste was recycled via the same route as the traditional one [16]. As the PLA recycling process ultimately transforms PLA waste to new PLA resin, the

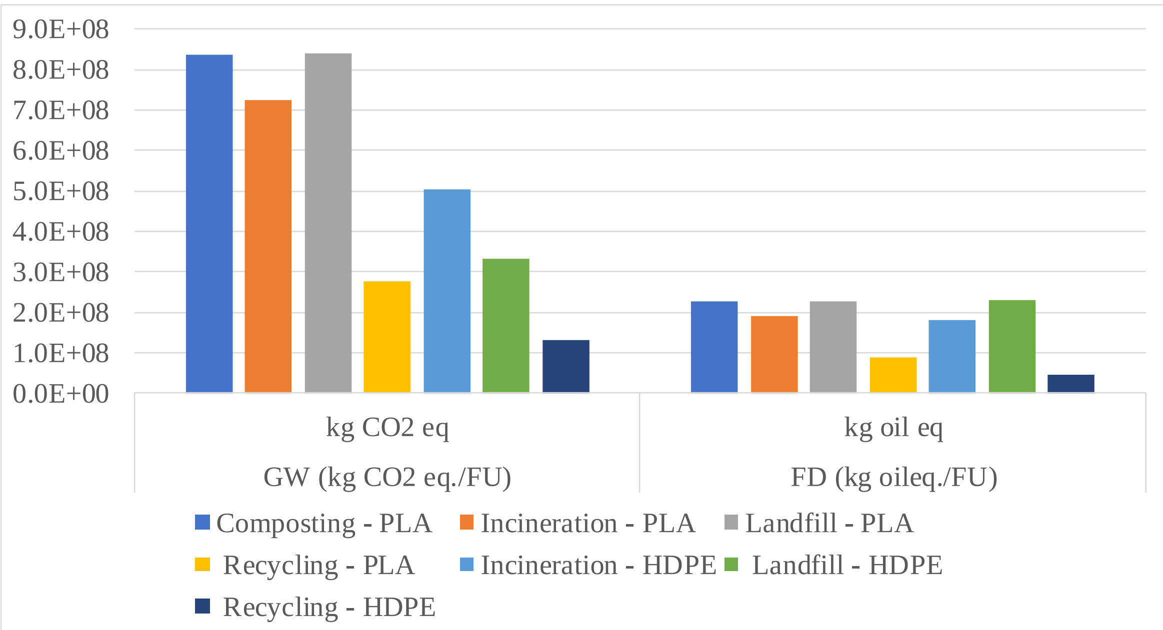

Figure 10. Environmental impacts of PLA and HDPE bags from cradle-to-grave (different disposal options).

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