Life Cycle Management for Plastic Waste Management: A Life Cycle Assessment of Polyethylene Bag in Thailand

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Abstract

This study applied life cycle assessment method for the evaluating the environmental impact of post-consumer polyethylene bag for food packaging. The system boundary was defined as the cradle-to-grave which included the production of ethylene, HDPE, LDPE and LLDPE resins and plastic bag, transportation and end-of life management. The results showed that most of environmental impact came from polyethylene resins production and raw material acquisitions including the energy consumption as well. The Strategies for mitigating the environmental impact of polyethylene bag for food packaging in order to achieve sustainability should cover the life cycle management of plastic bag product. For the raw material consumption, bio-materials and recycled plastic resins should be considered for the substitution of virgin material. For the production system, the 3Rs concept should be utilized in all production stages in order to increase the resource efficiency. For the end-of-life management, plastic waste should be recovered as a fuel for the substitution of coal instead of the incineration of municipal solid waste or landfilling method. This option can minimize the impact of global warming and non-carcinogen potential as well.

Keywords: *plastic waste management; 3Rs policy; waste management law and legislation*

1. Introduction

Nowadays, plastic has been utilized in many forms with various applications such as food packaging, household/industrial equipment and etc. As a result, the amount of plastic waste has been increased in a significant amount due to the increase in population and plastic consumption. The problems have become much more intense due to the poor degradability of general plastic (PCD, 2016). According to the database of waste from the department of marine and coastal resources of Thailand in 2015, the plastic bag contributed to the highest type of waste in the sea due to the poor waste management and human habit. PCD (2016) also claimed that most of plastic waste has to be eliminated by landfilling since 80% of plastic waste are contaminated and do not worth to be recycled due to the cost of elimination, collection and cleaning for these types of waste are not economic. Most of the plastic wastes consist of plastic bag and packaging which are composed of mainly High Density Polyethylene (HDPE), Low Density Polyethylene (LDPE) and Polypropylene (PP) (PCD, 2016).

With the increasing pressure to reduce the amount of plastic waste leakage to the sea, recycling of plastic waste is introduced for the political agenda in many developed countries. The agenda purposes are to reduce the amount of virgin material, energy consumption and also the amount of waste to landfill. In this case, the recycle processes should be applied without excessive energy expenditure (Barlow and Morgan, 2013). The minimization of raw material consumption along with plastic waste recycle utilization might be the most appropriate way to achieve the reduction in environmental impact (Siracusa et al., 2014). Among the recycle processes, mechanical process consumes the lowest amount of energy and resources. However, since this method is suitable for the high purity plastic waste, most plastic waste is categorized as low-value waste. Consequently, this process might not be acceptable due to uneconomic issue except the bottle recycling which is well-established as an economically viable process with the 39% recycling rates achieved in Europe (RECOUP, 2009).

Life cycle assessment (LCA) methodology is a technique used to evaluate the environmental impacts for various types of products. The scope of analysis covers the raw material extraction, production, consumption and disposal (Ruangrit et al., 2017). Wrap (2010) stated that most LCAs are assumed that the high quality of recyclable polymer waste could be substituted for the virgin polymer in a 1:1 ratio. In the other words, 1 kg recycled polymer could directly substitute for the 1 kg virgin polymer. Chaffee et al. (2007) concluded that the plastic bag from recycled HDPE could reduce the environmental impact by reducing the amount of plastic bag from the blending resin of polylactic acid (PLA) and EcoFlex. However, several researchers that involved various LCA options for the plastic waste disposal, including recycling technology showed that the characteristic of plastic waste was quite sensitive to the quality of the produced plastic. The substitution of virgin plastic is the preferred option when the separation process is in the high performance. In the case of contaminated and mixed plastics, the preferred options were the recovery of plastic as a fuel substitution for coal , the refuse derived fuel (RDF) or as a reducing agent in blast furnaces (Usapein and Chavalparit, 2014). Although it is well-known that the recycle of plastic waste has the potential for the reduction of non-renewable energy and global warming, it might increase the other environmental impacts such as aquatic ecotoxicity and respiratory inorganic. (Wrap, 2010; Simões et al., 2014). Frees (2002) also found that the excessive cleaning of food containers by using the hot water might consume the same amount of energy that gained from incineration of the containers.

Despite the fact that the environmental impact assessment of plastic products was utilized in various research works, most of them were aimed to determine only GHG emissions in the scope of cradle to gate (Treenate et al., 2017). Moreover, only few amounts of works were deal with the environmental impact of mixed polyethylene bag for food packaging. For this study, therefore, the environmental impacts of post-consumer plastic bags which are made from the mixing of HDPE and LDPE resin were evaluate through the life cycle assessment tool in the scope of cradle to grave. Consequently, feasible options are proposed according to the results of this study in order to encourage the global achievement of growing green properly.

2. Methodology

2.1 Goal and scope definition

The scope of this paper is to evaluate the environmental impact for 2 different types of post-consumer plastic bag for food packaging which are made from the mixed polyethylene resin; HDPE and LLDPE resin (case A) and LDPE and LLDPE resin (case B). Three scenarios of waste disposal were also studied which contained landfilling, waste to energy and incineration method. For each case, the calculations of LCA techniques are based on the ISO 14040 and ISO 14044 guidelines. The flowchart for the LCA of plastic waste can be shown in Fig. 1.

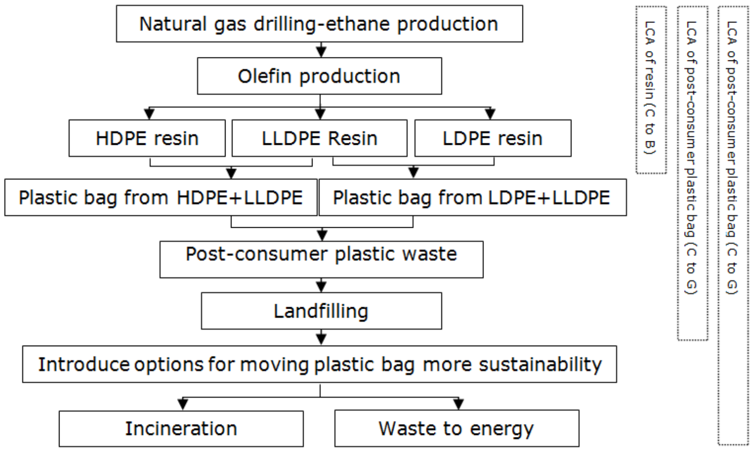

Fig. 1 Flowchart of LCA of plastic waste study

2.2 Functional unit and system boundary

- *Description of case A*

Case A involved the plastic bag for food packaging which is made from the blending of 50% HDPE resin and 50% LLDPE resin. The environmental impact was calculated based on 1 kg of plastic bag. The scope for determination involved the raw material acquisition, the plastic bag production, transportation and their end-of-life management. Since plastic food packaging are being contaminated and generally cannot be recycled. As a result, the post-consumer plastic waste are normally disposed by landfilling (PCD, 2016). The result from the heating value analysis (bomb calorimeter; ASTM 5865) showed that the embodied feedstock energy of this type of plastic waste was 42.24 MJ/kg. Consequently, this plastic packaging waste has the high potential for the RDF production or can be used as a fuel for energy recovery later on. The environmental impact was also calculated based on 1 kg of post-consumer plastic bags.

- *Description of case B*

Frozen food plastic bag made from the mixed polymer of LDPE and LLDPE. This type of bags are being produced by the blending of 20% LDPE resin and 80% of LLDPE resin. The environmental impact was also calculated based on 1 kg of plastics bag. Result from bomb calorimeter analysis showed that the embodied feedstock energy of this type of plastic waste was approximately 45.27 MJ/kg. The scope of determination was started from raw material acquisition to the end-of-life management.

2.3 Data inventory

Life cycle inventory of data resources, material and energy consumption of plastic bag can be classified from the phase of life cycle which are the raw material acquisition and pre-processing, plastic bag production, consumption and waste disposal were gathered from relevant sources. All natural resource inputs and emissions data from the value chain of a petrochemical industry (e.g. the olefin production, polyethylene (HDPE, LDPE and LLDPE resin) production and plastic converter factories (e.g. plastic bag production) in Thailand were gathered on-site as shown in Fig. 2. These types of data are the raw material, natural resource consumption (energy, water, and chemicals), waste generation and transportation. Consequently, since the consumption of plastic bag do not cause any additional harm, neither the data nor impacts were being collected and estimated. Finally, the data of plastic waste disposal phase were collected from stakeholder interviews and were used for the analysis by SimaPro V.8.2 with the background data contained in Ecoinvent V.3 database.

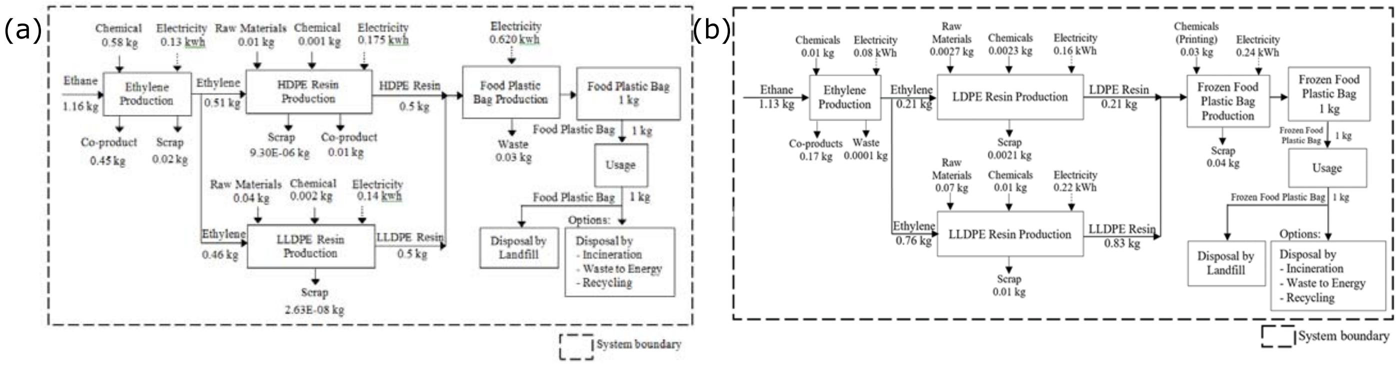

Fig. 2 System boundary of a plastic bag making from mixed polyethylene resins;
(a) Plastic waste from HDPE+LLDPE resin (b) Plastic waste from LDPE+LLDPE resin

2.4 Life cycle impact assessment

All the inputs and outputs were allocated to be based on 1 kg of plastic bag before the assessment of the environmental impact by the SimaPro software. The processes were extrapolated from Impact 2002+ V.2.12 method along with the Ecoinvent V.3 database within the SimaPro software version 8.2 for the identification of all the involved processes and materials. The results could be expressed in the quantity per the functional unit of 15 midpoint environmental impact categories. These impacts are Carcinogens (CA), Non-carcinogens (NCA), Respiratory inorganics (RI), Ionizing radiation (IR), Ozone layer depletion (OD), Respiratory organics (RO), Aquatic ecotoxicity (AE), Terrestrial ecotoxicity (TE), Terrestrial acidification/nitrification (TA), Land occupation (LO), Aquatic acidification (AA), Aquatic eutrophication (AU), Global warming (GW), Non-renewable energy (NR) and Mineral extraction (ME). In addition, the normalization was applied in order to analyze the contribution of each factor to the environmental performance with different scenarios of waste management.

3. Results and discussion

3.1 Environmental impact of polyethylene resin

The characterization factors were used to quantify the contributions of the difference processes for each impact category and the normalization were carried out to yield the reliable estimations (Gu et al., 2017). The comparison among the three polyethylene resins were carried out on the level of the endpoint method. Fifteen normalized results of 1 kg resin were presented in Fig. 3. All of the environmental impact from all types of polyethylene resins (HDPE, LDPE and LLDPE) were being analyzed in the same categories. It was found out that the combination of LDPE and LLDPE resin has higher impact compared with the HDPE for 8 categories. These impacts are CA, NCA, RI, RO, AE, TA, GW and NR due to the high energy consumption in production processes. While HDPE resins has higher impact on IR, OD, TE, LO and ME. This might results from the different type of raw material and chemical that are being utilized. For this work assumption, the polyethylene resin is produced from the ethane gas which is the clean raw material while HDPE resins use various kinds of raw material such as naphtha and LPG. Moreover, only the production of ethane gas the raw materials in the first stage of manufacturing was being considered for the environmental impact analysis as well.

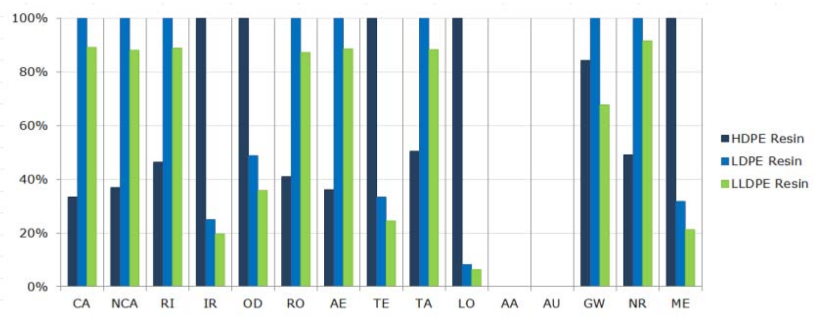

Fig. 3 Environmental impact among HDPE LDPE and LLDPE resin by End-point method

The results from the normalization showed that there were 5 significant environmental impact categories of the polyethylene resin which were CA, NCA, RI, GW and NR. For NR, the impact came from the high energy consumption in production processes as well as the feedstock energy embodied in the raw material. The high heating value for the HDPE, LDPE and LLDPE resin were in the range of 46.2-46.5 MJ/kg which contributed to 60-64% of energy consumption for production while the energy consumption for the resin production process was accounted for 35-38% of total energy consumption (ERG, 2011). For CA and NCA categories, it is known that ethane production and polymer production involves toxic organic substances. These organic substances associated with plastic production do not present a toxic threat in the consumption phase. Moreover, in natural gas extraction, heavy metal contamination in natural gas is eliminated during ethane production. Overall, the HDPE had the lower environmental impacts than the LDPE in every categories except the IR category. Moreover, several researches also reported that polyethylene resin has lower environmental impact comparing with the other plastic resins such as PET, PA, PP (Siracusa et al., 2011; Poovarodom et al., 2015).

3.2 Environmental impact of post-consumer of polyethylene bags

- *Midpoint characterization results*

The LCA results of the post-consumer plastic waste for food packaging for case A (HDPE+LLDPE) and case B (LDPE+LLDPE) showed that most environmental impacts came from the production of polyethylene resins which were used as the raw materials for plastic bag production. For all categories except OD, TE and LO, the highest environmental impact was generated from raw material acquisition and polyethylene resins production (HDPE, LDPE and LLDPE) as shown in Fig. 4(a). For the second stage of manufacturing, the pellets conversion process contributed less environmental impact. However, the amount of impact still could not be ignored. The obtained results were mostly agreed with the other research works (Wrap, 2010; Siracusa et al., 2014). The OD category was came from the solvent utilization in color printing as well as from frozen food plastic bag manufacturer (65.74%) while TE was mainly came from transportation (72.6%).

The end-of life management by landfilling for plastic bags could also have the significant impact on the LO, AU and GW categories as shown in Fig. 4(a). It can be concluded that production of polyethylene resins could have significant environmental impacts in almost every categories. As a result, the environmental impacts of post-consumer plastic bags could potentially be influenced from raw material production.

Despite the environmental impact from plastic bag production contributed to all categories, the OD, AU, GW and ME categories showed the significant impacts in which the plastic bag production is an energy (electricity) intensive processing step which emit the hydrocarbon carbon dioxide and nitrogen oxide.

Based on the environmental performances in different scenarios, the disposal of plastic bag by landfilling was highlighted for land occupation, as shown in Fig. 4(a). In addition, another plastic waste management option, in this case, the incineration generated high impact of global warming and non-carcinogen due to CO_2 emission including the heavy metal in the form of ash, as shown in Fig. 4(b). However, plastics waste can be incinerated with the energy recovery due to the high energy content and can be converted to electricity. This option could minimize the impact of global warming as shown in Fig. 4(c). Once the feedstock is converted to a product, there is the energy content that could be recovered. For example, from combustion in a waste-to-energy waste disposal facility. The maximum amounts of energy could potentially be recovered from combustion of the plastics. Vitale et al. (2018) studied the LCA of different valorization of package food wastes. The results showed that the energy recovery process provided the benefits in almost all the categories, due to avoidance of energy production thanks to the incineration process (apart from GW, OD and the TE impact categories). It was proved that the sorting and an EOL valorization of packaging food waste could give the environmental benefits compared to the landfill disposal.

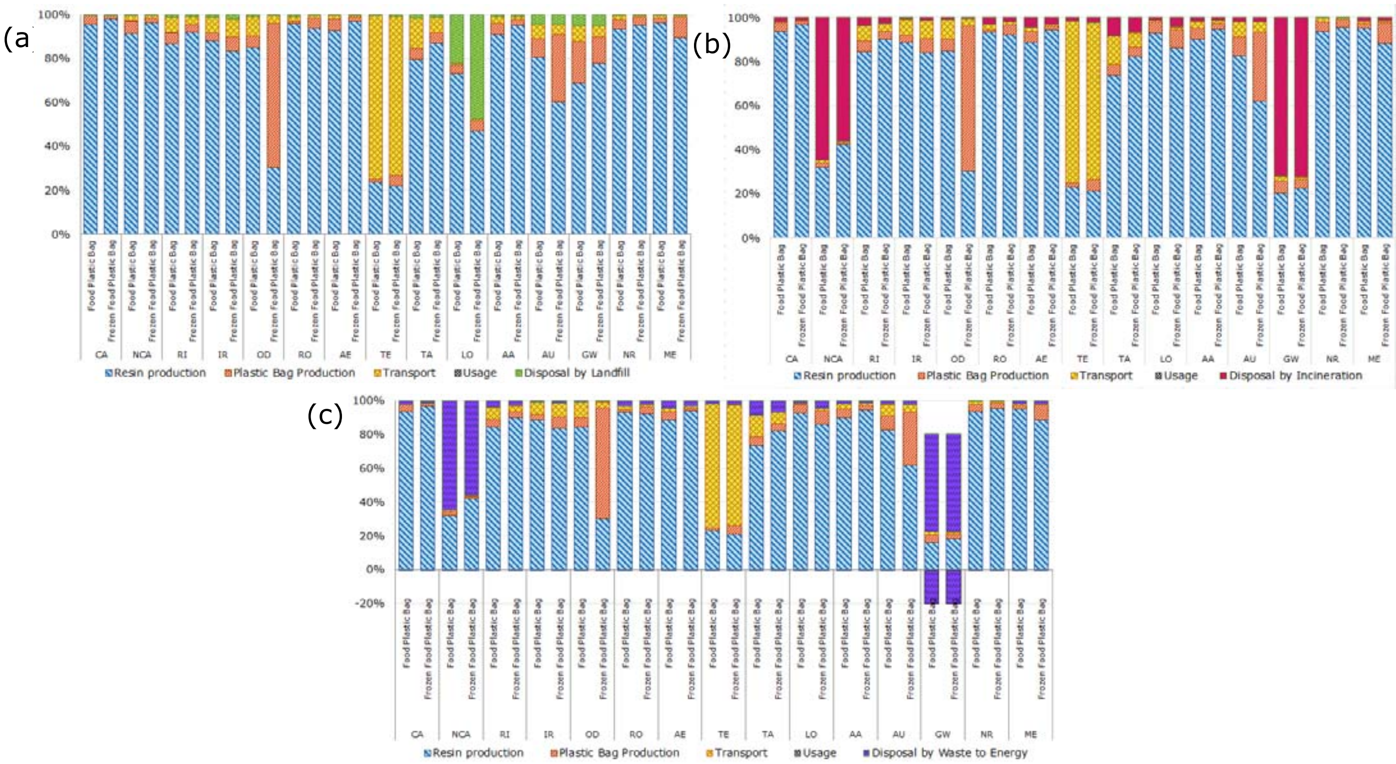

Fig. 4 Environmental impacts contribution in different scenarios of waste management: (a) Disposal by landfill (b) Disposal by incineration and (c) Disposal by waste to energy

- *End-point normalization*

The results obtained from the normalization of impact categories were shown Fig. 5. Five significant environmental impact categories which are NR, CA, RI, GW, and NCA were used for the analysis. Plastic bag of case B had higher environmental impact for all categories. Plastic bag waste disposal by municipal incineration contributed the highest impact compared with the disposal by waste to energy and landfill method, especially for GW category.

The comparison of environmental impact from cradle to grave between two polyethylene bags of case A and case B on the level of the endpoint method can be shown in Fig. 5. The results from normalization showed that NR contributed the highest impact category followed by CA, GW, RI and NCA. It was noted that non-renewable energy related directly to energy consumption in every stages of plastic production from the natural gas drilling, ethane production, ethylene production, resin productions, and energy for all processes. The feedstock embodied energy was concerned due to the fossil fuels consumption as raw material feedstock since most of energy consumption for plastic packaging comes from the feedstock energy. The results in a scope of cradle to gate, covering raw material acquisition and plastic bag production phase showed that NR category of case A came from LLDPE and HDPE resins production 61.9% and 32.1%, respectively and 9.5% from electricity consumption for resin and plastic bag production. The NR results of case B came from LLDPE and LDPE resins production 74.9% and 20.7%, respectively and 5.2% from electrictity consumption. GW category generated from energy consumption in all stages of plastic production and fuel consumption for transportation. The GW resulted from energy consumption in food plastic bag production of case A contributed for 37.6%, 35.2% and 33.1% from LLDPE resin production, HDPE resin production and electricity consumption, respectively. The GW results of case B came from LLDPE and LDPE resins production 63.7% and 18.3%, respectively and 25.3% from electrictity consumption. For the other impact categories such as: CA, NCA and RI of case A, the impact were mainly generated from LLDPE resins production 58.5-70.2% and HDPE resins production 25.3-29.3%. Furthermore, RI came from fuel consumption in transportation 5.5%. The CA, NCA and RI results of case B came from LLDPE and

LDPE resins production 72.7-76.4% and 20.3-21.9%, respectively and RI came from fuel consumption in transportation 3.39%.

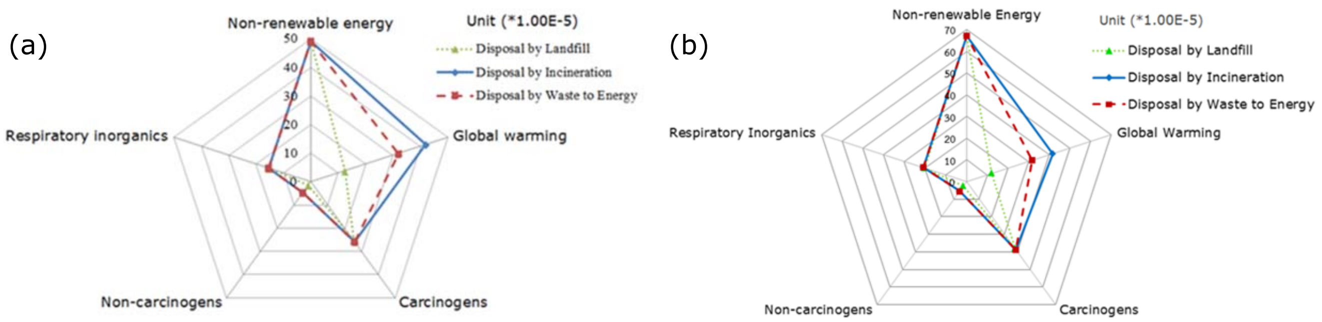

Fig. 5 Radar chart of environmental impact from plastic bag life cycle:
(a) Plastic bag from HDPE+LLDPE resin and (b) Plastic bag from LDPE+LLDPE resin

3.3 LCA of end-of life management

Based on the environmental performances in different scenarios, the disposal of plastic bag by landfill was highlighted for land occupation, as shown in Fig. 4(a). In addition, another plastic waste management option is incineration which generated high impact of global warming and non-carcinogen due to CO_2 emission and heavy metal in ash, as shown in Fig. 4(b). However, plastics waste have high energy content that can be incineration with energy recovery and converted to electricity. This option can minimize impact of global warming as shown in Fig. 4(c). Once the feedstock is converted to a product, there is energy content that could be recovered, for instance through combustion in a waste-to-energy waste disposal facility. The maximum amounts of energy that could potentially be recovered from combustion of the plastics. Vitale et al. (2018) study LCA of different valorization of package food waste. The results showed that the energy recovery process provides benefits in almost all the categories, due to avoided production of energy thanks to incineration (apart from Global warming, Ozone depletion and the Ecotoxicity impact categories. It was proved that the sorting and an EOL valorisation of packaging food waste can give environmental benefits compared to disposed of in landfill.

3.5 Alternative options for sustainable plastic bag waste management

Results from the LCA study emphasized that the major environmental impacts from post-consumers polyethylene bag for food packaging came from polyethylene resin production and raw material acquisition. As a result, the options for the polyethylene food packaging in order to achieve sustainability should cover the life cycle management as following:

- *Raw material level:*

a. *Biomaterial utilization*. Most food packaging waste is contaminated from food. As a result, using the packaging made from biomaterial is a good alternative for reducing the impact from non-renewable resources consumption and waste accumulation in the landfill (Barlow and Morgan, 2013). Poly lactic acid (PLA) which derived from the plant can play an important role in reducing the environmental impacts. Production of PLA packaging has a higher environmental footprints than the production of petroleum based polymer (Song et al., 2009). In addition, the environmental impact can also be reduced if the recycled material is used for composting (Pilz et al., 2010). However, this method is non-economic and might affect the food security (Treenate et al., 2017). Currently, Bioplastic comprises a small proportion of the total polymer consumption in Thailand.

b. *Virgin material substitution with recycled material.* Polymers are energy-intensive to manufacture (in the range of 70–100 MJ per kg) and most of them are derived from the fossil fuels. The mechanical recycling is the most suitable method for the high purity waste-streams of plastic waste (Barlow and Morgan, 2013). Recycled plastics can be regarded as a renewable source of material and could potentially reduce GHG emission. Moreover, LCA of mechanical recycling indicated that the environmental impact categories related to energy consumption, including global warming potential, acidification potential, eutrophication potential, abiotic resource depletion potential and residual solid waste generation were all decreased (Lazarevic et al., 2010). The LCA results revealed that the extrusion process contributed the highest environmental impacts, followed by the utilization of fillers and additives (Gu et al., 2017). Substitution of normal plastics with recycled plastics has been proved to be economic , practical and has environmental advantage (Kozderka et al., 2016). Despite the advantages of mechanical recycling plastic waste, recycling of plastics is still on a low level. The applicability of a plastic waste for products need to be assessed case by case due to the product unique requirements (Dahlbo et al., 2018). The normal material substitution ratio and the amount of organic contamination could also have a negative impact on the environmental benefits compared with the incineration with energy recovery as well (Lazarevic et al., 2010).

- *Production level:*

Since the major environmental impacts come from raw material and energy consumption in production stage, the 3Rs concept should be applied in order to increase the resources efficiency. The basis of sustainable waste management are applied and proposed as following;

a. *Minimizing the thickness of plastic bag.* Reduce the film thickness could reduce the amount of material consumed and energy for production and transportation (Barlow and Morgan, 2013).
b. *Renewable energy.* The promotion of alternative energy development such as solar, wind, biomass, biogas, is crucial (Treenate et al., 2017).
c. *Energy conservation.*The energy conservation measures for Thai petrochemical industry could be categorized into the six following categories: 1) steam saving and steam loss reduction, 2) steam optimization, 3) co-generation, 4) power saving by efficient chillers, 5) energy efficiency, and 6) waste energy recovery. The results showed that from the energy and environmental perspectives, the co-generation is the most capable of reducing energy consumption and greenhouse gas emission which accounted for 82% of the total reduction, followed by the waste energy recovery and energy efficiency categories. From economic point of view, the most cost effective measure category was steam saving and steam loss reduction, followed by waste energy recovery and energy efficiency categories (Tantisattayakul et al., 2016a; Tantisattayakul et al., 2016b; Usapein and chavalparit, 2017).

- *End-of-life management:*

For contaminated plastic waste, the utilization as a fuel in substitution of coal is the environmentally preferable option. Lazarevic et al. (2010) also stated that the utilization of plastic waste as solid recovery fuel in cement kilns was preferred rather than the incineration of municipal solid waste while municipal solid waste incineration proved to be a preferred option for most impact categories except for global warming potential when compare with the landfilling method.

4. Conclusion

The environmental impact of the polyethylene resins (HDPE, LDPE and LLDPE) were mainly determined by the production of ethane gas as the raw materials in the first manufacturing stage which depended on the impact category considered. Results from the normalization showed that there were 5 significant environmental impact category the polyethylene resin: CA, NCA, RI, GW and NR. Environmental impact of raw material (HDPE, LDPE and LLDPE resins) contributed to the highest potential for all impacts in line with the midpoint result. Therefore, the hotspot of environmental impact of plastic bag life cycle was polyethylene resin production and energy consumption in all stage of production. As a result, the options for moving polyethylene food packaging to sustainability should be cover the life cycle management. In the case of contaminated and mixed plastics, the environmentally preferable options were recovery as a fuel in substitution of coal or the production of refuse derived fuel (RDF) or as a reducing agent in blast furnaces.

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