LIFE CYCLE ASSESSMENT: CASE STUDY BOTTLE AND ADIPIC ACID PRODUCTION

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ABSTRACT

Life Cycle Assessment (LCA) is an important tool to calculate and to assess potential environmental impacts. The aim of this study is to illustrate the use of LCA in (1) comparing the production of Polyethylene terephthalate (PET) and Polycarbonates (PC) water-filled bottles and (2) comparing 2 scenarios in adipic acid production namely incinerate lignin and sell the lignin as byproduct. OpenLCA software has been used for LCA calculations. The LCA calculations estimate a number of environmental impacts such as photochemical oxidation potential, eutrophication potential, global warming potential, acidification potential, ozone depletion potential, and delpetion of fossil fuels. This study demonstrates the use of 4 standard steps in an LCA study: goal and scope definition, boundaries definition and functional unit, inventory analysis (LCI) and impact assessment (LCIA). For the bottle production case study, the LCA results showed that PET bottle production in general has lower environmental impact than PC. For the adipic acid production, "incinerate the lignin" scenario to substitute a portion of energy demand in adipic acid production in general gave lower environmental impacts than selling the lignin. This study reveals the role of LCA as a decision making tool to evaluate a production process by using life cycle principles. As a result, better assessment of environmentally friendly products or processes can be made.

KEYWORDS: Life Cycle Assessment, OpenLCA, Bottle Production, Adipic Acid Production

INTRODUCTION

There has been an increasing awareness to assess the environmental impacts of a product or process. The assessment of mass and energy flow during the life cycle of a "product" or "service" may indicate the amount of emission and waste that influences the environment. Without proper management, waste may have adverse impacts to the environment. Similarly, the use of fossil fuels during production processes leads to an increase of pollutants concentrations in atmosphere such as CO2, SO2, and NOx. A quantitative as well as systematic analysis is needed to determine the environmental impact associated to the various stages of a "product's life" (Bauman dan Tillman, 2004). This analysis is known as Life Cycle Assessment (LCA).

LCA assesses or calculates the environmental impact of a product or service life cycle holistically with concept from cradle to grave as a basis for decision making tool. The boundary of an LCA study should be determined. A cradle to grave LCA study may start from extraction raw materials, product manufacturing, packaging and marketing processes, and the use, re-use and maintenance of the product, and on to its eventual recycling or disposal as a waste at the end of its useful life (UNEP,1999 and ISO 14041, 1998). LCA is also a tool to guide technological development, and can be used to assess the environmental impact at the beginning of the product or service development process (Gontia and Janssen, 2016).

The result of an LCA study may tell us which part of a product lifecycle contributes most to the pollution, how the pollution occurs and guide us to take an appropriate action to solve the problem. LCA has been used in many fields such as solid waste management, power system, enzyme production, electricity generation technologies (Liamsanguan and Gheewala, 2008; Siddiqui and Dincer, 2017; Feijoo et al., 2017; and Ding et al., 2017).

This study demonstrates the use of LCA to calculate the environmental impacts of water bottle production (case 1) and to compare scenarios of lignin handling in adipic acid production (case 2). The case 2 is a simplified version of LCA study of adipic acid production presented by Aryapratama and Janssen, 2017. These 2 cases are materials from LCA 2 days training held by Chemical Engineering Department on Nov 30th-Dec 1st 2016.

Case 1 investigates the LCA of plastic bottles. LCA of plastic bottle is a classic example and hence it may serve well as an entry point in an LCA study. Plastic bottles are found in our daily life. The use of plastic bottles has more adventageous than other types of bottles such as glass bottles due to better resistance level (Lord, 2016). There are many types of plastics and each type is formed using different materials and processess depending on its usage. Plastic bottles are used to store water, oil, milk, shampoo, liquid soap, ink, softdrink and many others. Some examples of plastic bottles materials are: Polyethylene Terephthalate (PET), Polycarbonate (PC), High Density

Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low Density Polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS), dan etc. Here, the use of PET bottles and PC bottles is compared.

Case 2 investigates the LCA of simplified version of adipic acid production. Adipic acid is an organic compound which is used as nylon base material, monomer for the production of polyurethane, reactants to form plasticizers and lubricants, and flavorings (Kruyer and Yahya, 2017). Adipic acid production emits significant amount of N2O which is one of major greenhouse gas (Aryapratama and Janssen, 2017).

In this study, adipic acid is produced from lignocellulosic materials such as wood residue. In order to handle the lignin (the byproduct), there are two scenarios for lignin handling namely: (1) burned the lignin in incinerator to generate steam and (2) sell the lignin.

The aim of this study is to conduct LCA computations for case 1 and 2 by using LCA standard method. In addition, the use of OpenLCA as an open source software for LCA is also presented. OpenLCA is an open source software for Life Cycle Assessment (LCA) and sustanability assessment. It can be used for various applications:

1. Environmental Life Cycle Assessment (LCA)
2. Economic Life Cycle Costing (LCC)
3. Social Life Cycle Assessment (social LCA)
4. Carbon and water footprint
5. Design for Environment (DfE)
6. Environmental Product Declaration (EPD).
   (OpenLCA, 2017)

We hope that this paper may demonstrate the basic concept of LCA computation using a standard software as well as to stimulate LCA researches in Indonesia.

MATERIALS AND METHODS

As described earlier, LCA computation is conducted on OpenLCA software. This is an open source program which is developed by Green Delta Germany (www.openlca.org). The standard methods for an LCA study is going to be demonstrated here:

- **Goal and Scope Definition**

The objective of this study is to evaluate the environmental impact of two case studies.

Case 1: PET vs PC bottle

The first case focuses on comparing PET and PC bottle production. The goal is to determine which bottle is more environmentally friendly by comparing the production stages of PET and PC bottle.

Case 2: Incinerates vs sell lignin

The second case compares the insineration and sell the lignin options in adipic acid production. The goal is to determine which scenario is more environmentally friendly to handle lignin.

Fig 1 and Fig 2 illustrates the production processes for case 1 and case 2, respectively. Inventory analyses were conducted in each of production stage.

- **Boundary definition and functional unit**

Case 1: PET vs PC bottle

As seen from Fig. 1, PET and PC bottles production consist of 3 main stages: Granulate production, Transportation, and Filling. The functional unit used in this study is 1 unit of bottle product with the volume of 1 L water.

The only difference between PET and PC bottle is the raw material in granulate production. The transportation as well as bottle filling stages are identical for PET and PC bottle. Table 1 shows the raw material of PET and PC bottle.

Case 2: Incinerates vs sell lignin

Adipic acid production consist of 3 main stages: Pretreatment, Hydrolysis and Fermentation, and Downstream process (Fig.2). For the first scenario, the energy from lignin incineration can be used for process energy in the downstream process (Fig.2). As a result, the use of fossil fuels to generate steam can be reduced. Following assumptions were made for this case: the lignin heat content is estimated as 24 MJ/kg with lignin combustion efficiency of 80%.

The second scenario is to sell the lignin and hence lignin is used outside the boundary system. The price of lignin and adipic acid is 300 Euro/ton and 1800 Euro/ton, respectively. To compare scenario 1 and 2, the functional unit used in this case is 125 kg of adipic acid product.

- **Life Cycle Inventory (LCI)**

The Life Cycle Inventory (LCI) is intended to build a system model based on the needs that exist on goal and scope definition. Inventory analysis in both cases is based on input and output materials in a system: raw materials, resources, energy/electricity, air, distance, transportation, and emissions related to the functional unit. Besides, it also used a number of free databases which is associated to OpenLCA software. Here, we used Joint Research Centre (JRC) database and NREL database of US DoE.

Case 1: PET vs PC bottle

PET bottle is made from several types of materials such as Polyethylene terephthalate (PET) granulate, polyethylene high density (PE-HD) granulate and Polypropylene (PP) granulate. On the other hand, PC bottle is made from several materials such as polycarbonate (PC) granulate, Polyethylene low density (PE-LD) granulate, and Polybutadiene (PB) granulate. The inventory data used is shown in Table 1.

Case 2: Incinerates vs sell lignin

Fig 3 shows the simplified diagram of mass and energy flows in adipic acid production. Here, 1400 kg of wood residue with 21.43% of lignin content is fed to the system. The wood is pretreated using steam explosion. The amount of steam demand is 1700 kJ/kg Dry Material (DM). The steam is generated by using fossil fuel mix consists of natural gas (86%) and heavy fuel oil (14%), with 85% efficiency. It is assumed that the wood residue collection area is located near the plant, so the impact from the transportation is negligible. About 6000 liter of water is added per 1400 kg of treated wood residue (50% DM).

An additional 6000 l of water is added for hydrolysis and fermentation processes. Enzyme (8.2 g/kg DM) is used to hydrolyze the pretreated wood (Table 2). The emissions-related data generated from the enzyme production process are summarized in Table 3. It is assumed that there are only minor impacts from the nutrients, microorganism and electricity demand in fermentation process, and thus it can be neglected. Further, it is also assumed that the lignin is completely unfermentable.

In the downstream process, adipic acid is separated during several subsequent separation processes with water and other byproduct (lignin and undigested residual materials). According to the simulation result, the steam demand in downstream process is 39.1 MJ/kg adipic acid (the same fossil fuel mix and efficiency as in the pretreatment process is also applied here). It is assumed that the separation process is highly efficient. As a result, for every

1400 kg (50% DM) of feedstock, about 125 kg of adipic acid can be produced. The undigested residual materials along with process water are sent to the wastewater treatment plant (outside of system boundary).

RESULT AND DISCUSSION

- **Life Cycle Impact Assessment (LCIA)**

The environmental impact is estimated using CML (baseline) method. A number of environmental impacts such as global warming (GWP), ozone depletion (OD), toxicity (Tox), acidification potential (AP), eutrophication (Eutroph), formation of photochemical oxidants (FPO), and depletion of abiotic resources (DAR) were estimated. Table 4 below shows the LCIA from the selected LCIA method.

Case 1: PET vs PC bottle

Table 5 shows the results from LCIA computation of PET and PC bottle for each functional unit. By comparing PET and PC, it can be seen that PET has generally lower environmental impact than PC bottle. Hence, PET bottle in this case is better than PC at least based on the boundary system chosen here.

Case 2: Incinerates vs sell lignin

Table 6 shows the LCIA comparison of both scenarios in lignin handling. As seen here, incineration of lignin to substitute a portion of energy demand (scenario 1) gave lower environmental impact than that of selling the lignin (scenario 2). Hence, scenario 1 is more preferable as the option to handle lignin in this case.

By comparing the number in Table 6, it is clear that the GWP as well as depletion of fossil fuels impact of scenario 1 is significantly lower than scenario 2. Hence, the impact of fossil fuel use here is significant and replacing them by incinerating lignin turns out to be a promising alternative.

CONCLUSION

LCA is a useful quantitative method to calculate the environmental impact of a product's lifecycles. The use of open source software and databases for simple LCA case studies have been presented. For case 1, LCIA results from PET and PC water bottle production showed that PET bottle gave lower environmental impact than that of PC bottle. In the 2nd case, two scenarios for lignin handling have been demonstrated. Scenario 1 of lignin incineration to substitute the use of fossil fuel gave lower environmental impacts than the scenario 2 of selling the lignin. The impact of fossil fuel replacement is clearly seen here by comparing the GWP and depletion of fossil fuel potential.

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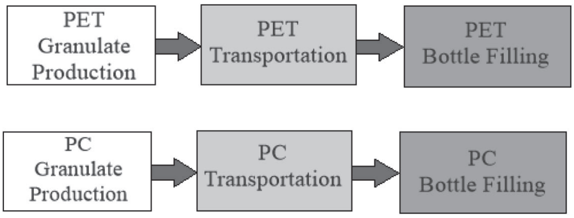

Fig 1. PET and PC bottle production

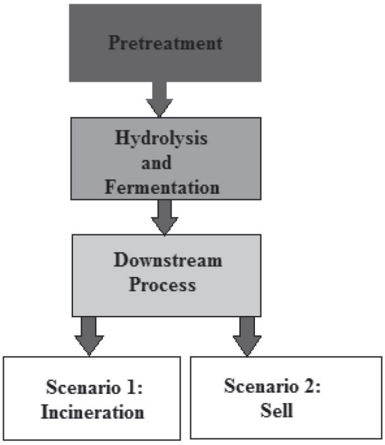

Fig. 2 Adipic acid productionBoundaries Definition and Functional Unit

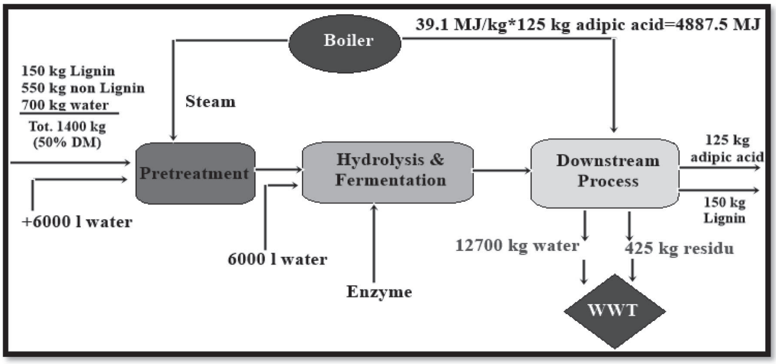

Fig. 3 Adipic acid boundary system

List of Tables:

PET Bottle Production			*PC Bottle Production*		
PET Granulate Production	Polyethylene terephthalate (PET) granulate	60 g	*PC Granulate Production*	polycarbonate (PC) granulate	60 g
	polyethylene high density (PE-HD) granulate	4 g		Polyethylene low density (PE-LD) granulate	4 g
	Polypropylene (PP) granulate	1 g		Polybutadiene (PB) granulate	1 g
PET Transport A	Granulates (PET, HDPE, PP)	0.065 g	PC Transport A	Granulates (PC, LDPE, PB)	0.065 g
	Transport in t*km	0.000065 t*500 km		Transport in t*km	0.000065 t*500 km
PET Bottle Filling	Granulates (PET, HDPE, PB), transported	1 item	PC Bottle Filling	Granulates (PC, LDPE, PB), transported	1 item
	Drinking water	1 kg		Drinking Water	1 kg

Table 1. Lifecycle inventory of Case 1

Tabel 2. Life cycle data for enzyme production (Liptow et al, 2013)

Impact	Potential	Unit
GWP^{a}	9,000	g CO_2 eq/kg enzyme product
ACP^{h}	56.0	g SO_2 eq/kg enzyme product
POCP^{c}	3.8	g ethylene eq/kg enzyme product
EP^{d}	15.0	g PO_4 eq/kg enzyme product
Fossil energy	120	MJ/kg enzyme product

GWPa *global warming potential*
ACPh *acidification potential*
POCPc *photochemical ozone creation potential*
EPd *eutrophication potential*

Tabel 3. Emission data truck transport (Liptow et al., 2013)

Emission	Quantity	Reference
CO_2	0.06 kg/tkm	g CO_2 eq/kg enzyme product
NO_x	0.46 g/tkm	g SO_2 eq/kg enzyme product
HC	2.00x 10-2 g/tkm	g ethylene eq/kg enzyme product
CO	0.13 g/tkm	g PO_4 eq/kg enzyme product

Table 4. LCIA categories

Impact category	Unit
Acidification potential - average Europe	kg SO2 eq.
Climate change - GWP100	kg CO2 eq.
Depletion of abiotic resources - elements, ultimate reserves	kg antimony eq.
Depletion of abiotic resources - fossil fuels	MJ
Eutrophication - generic	kg PO4- eq.
Freshwater aquatic ecotoxicity - FAETP inf	kg 1,4-dichlorobenzene eq.
Human toxicity - HTP inf	kg 1,4-dichlorobenzene eq.
Ozone layer depletion - ODP steady state	kg CFC-11 eq.
Photochemical oxidation - high Nox	kg ethylene eq

Table 5. LCIA for case 1: PET vs PC bottle production

	PET	PC	Unit
Photochemical Oxidation Potential	$6{,}39\ 10^{-5}$	$1{,}1\ 10^{-4}$	kg ethylene - eq
Eutrophication Potential (EP)	$6{,}49\ 10^{-5}$	$1{,}8\ 10^{-4}$	kg PO_4 – eq
Global Warming Potential (GWP)	$2{,}08\ 10^{-1}$	$4{,}78\ 10^{-1}$	kg CO_2 – eq
Acidification potential (AP)	$9{,}9\ 10^{-4}$	$1{,}55\ 10^{-3}$	kg SO_2 - eq
Ozone Depletion Potential (ODP)	$8{,}8\ 10^{-12}$	$8{,}8\ 10^{-12}$	kg CFC-11 eq.
Depletion of abiotic resources – fossil fuels	4,61	6,36	MJ

Table 6. LCIA for case 2: incinerate vs sell lignin in adipic acid production

	Incinerate (Scenario 1)	Sell (Scenario 2)	Unit
Photochemical Oxidation Potential	$1{,}24\ 10^{-3}$	$1{,}26\ 10^{-3}$	kg ethylene - eq
Eutrophication Potential (EP)	$2{,}21\ 10^{-3}$	$1{,}54\ 10^{-3}$	kg PO_4 – eq
Global Warming Potential (GWP)	3,18	4,12	kg CO_2 – eq
Acidification potential (AP)	$1{,}8\ 10^{-2}$	$1{,}85\ 10^{-2}$	kg SO_2 - eq
Ozone Depletion Potential (ODP)	$8{,}16\ 10^{-10}$	$1{,}13\ 10^{-9}$	kg CFC-11 eq.
Depletion of abiotic resources – fossil fuels	42,33	59,07	MJ