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Life cycle assessment of non-alcoholic single-serve polyethylene terephthalate beverage bottles in the state of California

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ABSTRACT

The aim of this study was to evaluate the environmental burden of non-alcoholic single serving size polyethylene terephthalate beverage bottle systems in the state of California through a life cycle assessment model. A mass flow of polyethylene terephthalate beverage bottle in the U.S., and the state of California is drawn as a Sankey diagram. The life cycle assessment model is designed with five main sections; material production, polyethylene terephthalate bottle production, waste management, environmental benefit, and transportation. The scope is cradle-to-grave with a representative functional unit as the amount of polyethylene terephthalate necessary to deliver 1000 L of beverage, specifically in carbonated soda, water and tea. To identify the strategy to reduce the environmental burden of the overall system, several scenarios are established as the management intervention by reducing two different polyethylene terephthalate waste sources; post-consumer polyethylene terephthalate bottle collection waste, scenario 'c', and yield loss of the reclamation process, scenario 'r'. The contribution analysis indicates that the polyethylene terephthalate bottle production is the highest environmental burden source in most of the impact indicator. Scenario 'r' is translated in higher environmental benefit than the pursuit of scenario 'c' in every impact indicator. The results show that increasing efficiency of the reclamation process provides a larger environmental benefit than improving the post-consumer bottle collection system for polyethylene terephthalate beverage bottle in the state of California. The results can be used to comprehend the main environmental burden of polyethylene terephthalate bottles and to optimize their recovery in the other 49 U.S. states and around the world.

1. Introduction

In 2013, a total of 195 billion beverage packaging units were sold in the U.S., representing 178 billion U.S Dollars (Euromonitor International, 2013b). The state of California consumed about 11% of these total beverage-packaging units sold (CalRecycle, 2013). Fig. 1 shows that polyethylene terephthalate (PET) is the number one plastic, taking up to 39 billion units out of the total 195 billion units of the beverage packaging in the U.S. PET represented 44 percent of the total 21.3 billion units of beverage packaging consumed in the state of California in 2013 (CalRecycle, 2013; Euromonitor International, 2013a). Despite the high volume of beverage packaging unit sales, the US market has been saturated due to the decline in sales of carbonated soda drinks (CSD), reporting only 0.6 percent average growth rate (Euromonitor International, 2010). This trend resulted in a decrease of metal beverage packaging sales in the US, dropping from 85 billion units in 2008 to 81 billion units in 2013 (Euromonitor International, 2013a). In contrast, the US PET beverage packaging sales increased from 67 billion units in 2008 to 75 billion units in 2013 due to the increasing demand for bottled water, functional drinks, ready-to-drink tea, and flavored milk drinks delivered in PET containers (Euromonitor International, 2013b). The state of California consumes and recycles the largest numbers of bottles and cans in the US, (CalRecycle, 2013). With 2400 certified recycling centers, hundreds of curbside recycling programs (like the California Refund Value (CRV) program), California Beverage Container Recycling Litter Reduction Act and the California bottle bills, 74 percent of PET beverage bottles were recycled in California in 2013. As shown in Fig. 1, the average recycling rate of PET beverage bottle in California is twice that of the US average.

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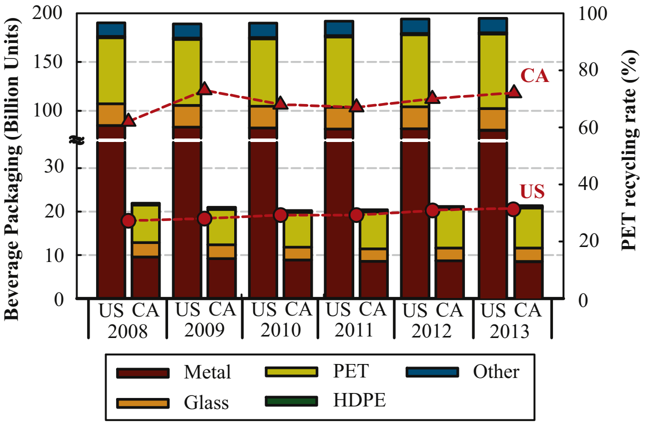

Fig. 1. Beverage packaging market in the US and the state of California; red triangle indicates the recycling rate of PET in the state of California, whereas red round circle indicates the PET recycling rate in the US, data obtained from Ref. (CalRecycle, 2013; Euromonitor International, 2013a; US EPA, 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Life cycle assessment (LCA) is a useful technique for analyzing the environmental footprint of products like PET beverage bottles at all stages in their life cycle – from the extraction of resources, through the production of materials, parts, and the product itself, and to the use of the product and its disposal, either by reuse, recycling, or landfilling with or without energy recovery (*i.e.*, "from the cradle to the grave") (Greene, 2014; Guinee, 2001). LCA is composed of four steps: goal and scope, inventory analysis, impact assessment, and interpretation of results. These steps are extensively described in the ISO 14040 and 14044 standards (ISO, 2006a, 2006b).

LCA of beverage packaging has been extensively conducted. Some of the studies were focused on the comparison of the different beverage packaging in terms of environmental performance (Amienyo et al., 2013; Franklin Associates, 2007; Gironi and Piemonte, 2011; Jelse et al., 2009; von Falkenstein et al., 2010). According to von Falkenstein et al. (2010) beverage carton has the lowest environmental burden compared to PET, high density polyethylene (HDPE), poly vinyl chloride (PVC) and glass beverage. On the other hands, Amienyo et al. (2013) concludes that PET bottles are the most sustainable option compared to glass bottles and aluminum cans.

Many studies have been conducted to support the decision-making on waste management of PET beverage bottle in different geographical regions, such as Romero Hernandez et al. (2009) in Mexico, Foolmaun and Ramjeawon (2008) in Mauritius, Coelho et al. (2011) in Brazil, Nakatani et al. (2010) in Japan, Papong et al. (2014) in Thailand, Perugini et al. (2005) in Italy, Song et al. (1999) in Korea, IFEU (2004) in Europe, Franklin Associates (2007, 2010) in the U.S., and Kuczenski and Geyer (2013) in California. Despite the different goals and system boundaries, the conclusion were similar that recycling is the most favorable option for beverage packaging producing the lowest environmental burden in the majority of the impact indicators. Chilton et al. (2010); Foolmaun and Ramjeawon (2008) and Perugini et al. (2005) reported that mechanical recycling is the best waste management option for plastic waste. Michaud et al. (2010) after screening 200 LCA studies published since 2006 also reported that mechanical recycling is the best waste management option for plastic waste including PET bottle. The environmental benefit on the climate change potential, depletion of natural resources, and energy demand impacts of mechanical recycling is mainly obtained from avoiding the production of virgin resins.

Plastic waste can be recovered in two ways; closed and open loop recycling. In LCA studies, closed loop recycling is handled by replacing the virgin material with recycled material, whereas in open loop recycling an increasing trend is to manage by the systems expansion method, which extends the system boundary hypothetically to include the environmental benefit of the recycled product. A number of studies have evaluated and reviewed the benefits of open loop recycling (Coelho et al., 2011; Frank, 2011; Li et al., 2010; Papong et al., 2014). Song et al. (1999) derived a mathematical model to manage the PET waste, and they determine that the overall optimal solution for PET waste management when considering energy conservation was collecting 80 to 90% of the PET bottle for closed loop recycling and incineration of the other bottles that were not collected for recycling. When considering CO_2 emission, the authors determined that the optimal scenario was 85% of PET bottles collected for closed-loop recycling with the remaining bottles sent to landfill. Chilton et al. (2010) expanded Song et al. (1999) models for PET waste management by including operational data such as transport-related emissions and burden associated with cleaning the recovered PET flakes. They also showed that recycling of PET results in a net reduction in the emission of CO_2, carbon monoxide, acid gases, particulate matter, heavy metals and dioxins, which is related to avoiding the production of PET virgin resin. Kuczenski and Geyer (2013) modeled the environmental impacts of PET bottle recycling under the California's CRV deposit program during 2007–2009. They found that the choice of reclaimer for post-consumer bottles is the most environmentally significant end-of-life decision. They also suggest that deposit programs on disposable packaging are a useful policy mechanism to improve environmental performance. Recently, Nakatani et al. (2010) provides a graphical representation and mathematical analysis of the life cycle inventory of open and closed-loop recycling of products.

Considering that the state of California recycles the largest number of PET bottles in the US and that CalRecycle can control, legislate, and incentivize the collection and recovery of PET bottle (CalRecycle, 2013), understanding the optimal environmental footprint of managing PET bottles in California could reduce the overall footprint of the PET bottles used in the state. In turn, this information could also serve as a model for optimizing the recovery of PET bottles in others of the US states. Therefore, the main objectives of this research were to: *i*) provide a mass flow scenario of PET bottle in the US and the state of California; *ii*) conduct a contribution and uncertainty analyses of the main environmental burden of the current PET bottle system in the state of California, and *iii*) determine which end of life scenario stage should be targeted for improvement to reduce the environmental footprint of PET bottles.

2. Experimental methods

The environmental savings in the life cycle stages of the PET beverage bottle was determined by first establishing a life cycle model of non-alcoholic single serve PET beverage bottle system in the state of California, including open and closed loop recycling and energy recovery with incineration and landfill as end of life. Using this model, a contribution analysis was performed to examine the main environmental impacts of the current PET bottle system. Based on the results of contribution analysis, two life cycle stages were identified where potential environmental improvement could be very high: post-consumer beverage bottle collection where some amount may be not collected or may not meet the quality to be recycled due to contamination (scenario 'c'), and yield loss of the recycling process (scenario 'r'). Management intervention was applied to these two life cycle stages by reducing the uncollected amount of post-consumer PET beverage bottle, which is referred as recyclable PET in this study, during post-consumer

Table 1
Parameter used in this study for recyclable PET; Parameter *i* indicate the source of recyclable PET acquired from PCB collection waste ($i = 1$) and yield loss of recycling process ($i = 2$). Parameter j represent the closed loop recycling ($j = 1$) and open loop recycling ($j = 2$).

r_{ij} : PET recycling contents		Source of recyclable PET
		$i = 1$ $i = 2$
Recycling route	$j = 1$ $j = 2$	r_{ij} : Recyclable PET $(i = 1, 2, j = 1, 2)$ $i = \begin{cases} 1 : \text{PCB collection waste} \\ 2 : \text{Yield loss of recycling process} \end{cases}$ $j = \begin{cases} 1 : \text{Closed loop recycling} \\ 2 : \text{Open loop recycling} \end{cases}$

beverage bottle collection and yield loss of recycling process, and used to hypothetically increase the total amount of recyclable PET to quantify the savings on the environmental footprint of PET bottles.

2.1. LCA scope and functional unit definition

The functional unit was defined as the amount of PET necessary to deliver 1000 L of beverage, specifically carbonated soda drink (CSD), water and tea. These three categories are taking 66.2 percent of total US non-alcohol beverage consumed (Beverage World, 2006). Ten bottles per each volume and each type of beverage were purchased at local retailers (in East Lansing, Michigan). The functional unit selected is a representative mix of the market in terms of volumes and types of beverages. Since the weight of single serving size PET beverage bottle varies depending on the type of beverage and their volume, equation (1) was applied to calculate the appropriate functional unit for this study. Size and weight of single serving size PET beverage bottles are similar across the U.S, so it was assumed that there were no statistically significant differences in weight and size of PET bottles used in Michigan and California. The beverage type considered in this study was carbonated soda drink (CSD), water and tea. Using the percentage of sales amount of each type of beverage in the Pacific region of the U.S. as weighing factor () (Beverage World, 2006), the functional unit of this study was calculated per each component; PET body (34.2 kg/1000 L) and polypropylene (PP) cap and PP label (8.4 kg/1000 L). Detail calculation of functional unit is explained in the Supporting information Figure A.1 .

$$F = \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{2}\alpha\frac{b_{ij}}{m_k} \qquad (1)$$

$$i = \begin{cases} 1 : \text{CarbonatedSoda} \\ 2 : \text{Water} \\ 3 : \text{Tea} \end{cases}, j = \begin{cases} 1 : \text{Body} \\ 2 : \text{Cap} \\ 3 : \text{Label} \end{cases}, k = \begin{cases} 1 = 591\ \text{mLvolume} \\ 2 = 500\ \text{mLvolume} \end{cases}$$

where b_{ij} = weight of beverage packaging component in *i th* beverage in *j th* component (kg), $m_k = k$ *th* volume of beverage packaging (liter), $i = i$ *th* beverage weighting factor, F_j = Functional unit of *j th* beverage packaging (kg/1000 L).

The system boundary of this study is ‘cradle-to-grave’, and in order to make a clear interpretation of the contribution analysis, it is discretionally divided into 5 main sections; 1. Material production, 2. PET bottle production, 3. Waste management 4. Environmental benefit and 5. Transportation. These five main sections were established based on the general PET bottle production (Lim et al., 2008). In the material production section, the inventory processes include extraction of natural resources, such as crude oil and natural gas, used for PET and PP resin production. PET bottle production includes injection stretch blow molding (ISBM) of the PET bottle, and extrusion and injection molding for PP label and cap, respectively. Waste management represents the environmental impact of waste landfill, incineration and recycling process. Environmental benefit accounts for the energy recovery generated by combustion of waste and recycled PET (material recovery) made through closed and open loop recycling. Transportation consists of transport of packaging material (PET and PP), post-consumer PET bottles (PCB) to collection facility, collected PCB to material recovery facility (MRF), and PET bale to reclamation facility. Detail descriptions of the inventory processes and stocks for each section are provided in Supporting information Table A. 1.

2.2. Key assumptions

The following assumptions were made to close the gap between the LCA models and the actual life cycle of the PET beverage bottle. Because some of the inventory data of PET beverage bottle is not available, several assumptions and limitations were taken into consideration.

- Technology development of PET beverage bottle production, such as lightweight bottle, is not considered in the functional unit.
- For delivering the amount of fluid requested by the functional unit of 1000 L, 548 CSD bottles, 1090 water bottles, and 135 tea bottles are required as shown in Figure A1 in the Supporting information available online.
- The majority of the processes of the life cycle of PET beverage bottles are performed in the US.
- The depreciation and environmental impact of existing infrastructures was excluded.
- The secondary and tertiary packaging of the PET beverage bottle were excluded.
- The environmental impact of the ink on the PP label and cap was considered negligible.
- The beverage production was excluded since it is not part of the functional unit of the study.
- All the PET and PP waste, except that handled by recycling, was assumed to be managed through incineration with energy recovery and landfill in a 20% and 80% ratio, respectively (Van Haaren et al., 2010).
- To consider the energy recovery during the end of life scenario from incineration of PET and PP waste, the heating value of PET bottles and PP caps/labels was estimated as 23,026 and 46,310 kJ/kg, respectively (Franklin Associates, 2009).
- Surfactant and wet agent used for the material recovery process (i.e., recycling) was treated as detergents, and modeled as sodium tripolyphosphate.
- Trucks used during the post-consumer PET bottle collection stages are assumed to be fully loaded coming into the facility and returned empty or with empty containers.
- PET preform and bottle were made at the same location, so transportation was not included in this stage.
- Most of the LCI data were employed from US-EI v2.2, which established based on European data with U.S. average electricity. Detail information of the LCI data is provided in the Supporting information Table A. 3 provided online.

2.3. Life cycle inventory analysis (LCI)

The source of data in this LCA was acquired from various literature, databases from SimaPro software (PRe Consultants 2011), like Ecoinvent V2.2. The details of data source (American Chemistry Council, 2012; CalRecycle, 2013; Davis, 2007; EarthShift, 2009; Franklin Associates, 2010; NAPCOR, 2010; NewPoint Group, 2009; US Census Bureau, 2007, 2012; US ITC, 2010) are provided in the Supporting information Tables A. 2 and A. 3.

For the material production section, database for PET bottle grade resin includes the production of ethylene glycol (EG), purified terephthalic acid (PTA), amorphous PET resin and solid-state polymerization. Also, energy input, waste, air, and water emissions of each step were included. For the PP resin, the Ecoinvent V2.2 provides aggregated data for all processes from raw material extraction until delivery at the plant.

ISBM, injection molding and extrusion molding was used to produce PET bottle, PP cap and label, respectively. ISBM contains the auxiliaries and energy demand processes. Ecoinvent V2.2 indicates 2.2% of yield loss during ISBM, while 0.6% and 2.4% yield loss occur in injection and extrusion molding, respectively. All theses yield losses are dealt with 20% incineration and 80% landfill.

The waste management section contains material recovery, reclamation process and solid-state polymerization for recycled PET as well as combustion and landfill for PET and PP waste. The data for material recovery and reclamation process was obtained from the report of Franklin Associates (Franklin Associates, 2010). Due to the lack of reported data, the LCI of the solid-state polymerization process for closed loop recycling was obtained from a Ref. (Dogan, 2008), which oversimplify the input of solid-state polymerization considering just the electricity (584–1260 kWh) and the cooling water (0.4–10 m^3). There are two sources of PCB collection; California Refund Value (CRV) and non-CRV. During the PCB collection, uncollected or low quality PCB goes to waste, and this waste was one of the variables to evaluate the impact on the LCA results. Another variable in this study was the yield loss during reclamation process. It was assumed that these two scenarios could potentially be improved in a waste management perspective.

In the environmental benefit section, all the activities to reduce environmental burden were included such as closed loop, open loop recycling and energy recovery generated from combustion of plastic waste. The PET amount of closed loop and open loop recycling was obtained from the report of the National Association for PET Container Resources (NAPCOR) (NAPCOR, 2010). For energy recovered by incineration, 23,026 and 46,310 kJ/kg of calorific value were used for PET and PP, respectively (Franklin Associates, 2009).

In order to evaluate the overall environmental burden of the transportation activities, the transportation section grouped the distribution of filled bottle, the PCB collection through three different collection methods (drop off center, curbside program and recycling center), PCB to MRF and MRF to reclamation facility. An average distance of 107 km (67 miles) was determined for filled PET beverage bottles from the 2007 commodity flow survey of the U.S. Census Bureau (US Census Bureau, 2007). The distance and amount of PCB collection by the three different collection methods was obtained from the report of Franklin Associates and the California Department of Resources, Recycling and Recovery (CalRecycle, 2011; Franklin Associates, 2010).

In addition, a Sankey diagram of the PET beverage bottle system in the U.S. and California in 2010 was drawn based on primary and secondary inventory databases. The Sankey diagram is considered an important aid in identifying inefficiencies and potential savings when dealing with resources. Thus, the LCA model, the scenario setup, and the parameters used in Fig. 2 were based on the Sankey diagram.

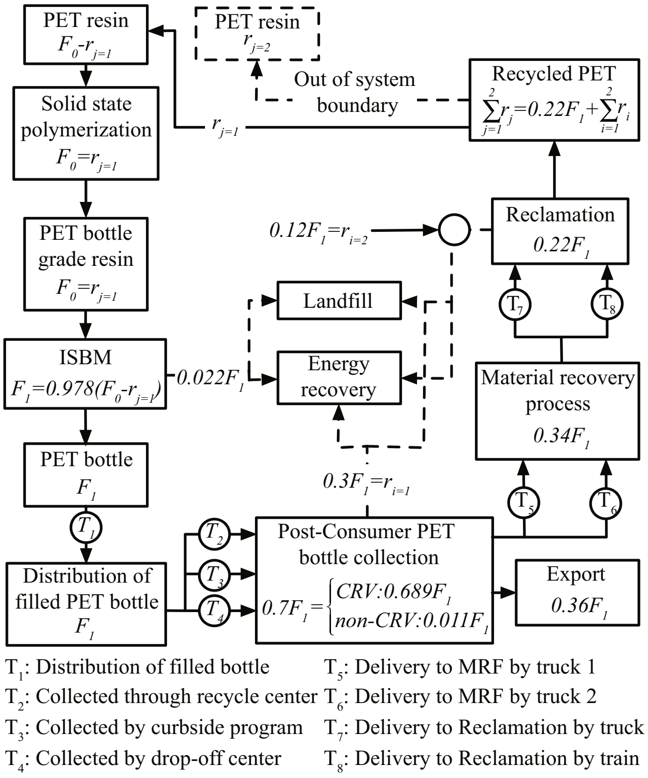

Fig. 2. Parameterized flow diagram of the life cycle of non-alcoholic single serving size PET beverage bottle.

2.4. Scenario setup

Generally, management intervention is applied to improve the system performance, especially environmental performance. Such an impact of intervention is often estimated by hypothetical scenarios. In this study, hypothetical situations were made based on two variables. Table 1 describes these variables; recycling route and source of recyclable PET. There are two different recycling routes; closed loop and open loop recycling. For closed loop recycling(= $r_{j=1}$), recycled PET from PET beverage bottle is going back to produce the PET beverage bottle. For open loop recycling(= $r_{j=2}$), also called down-cycling, recycled PET is used to produce products requiring lower quality PET resin, such as films and sheets than PET beverage bottle. Besides the recycled PET (22% of functional unit) in the current PET beverage bottle system, hypothetical scenarios were established to increase recyclable PET. Two sources are considered; PCB collection waste (= $r_{j=1}$) and yield loss of recycling process(= $r_{j=2}$).

The comparison of open and closed loop recycling scenarios revealed no statistically significant differences. The main difference between open and closed loop recycling was the latter's solid-state polymerization process which is done to increase the quality of recycled PET resin for bottles. This polymerization process produces higher intrinsic viscosity than the one used for PET fiber, film and engineering resin. However, the solid-state polymerization process of our study is oversimplified due to lack of primary data. For this reason, even though open and closed loop recycling are parameterized in this study, the EFP of recycled PET from these two recycling routes were found to be similar due to the lower EFP of solid state. This oversimplification will need further evaluation in future works.

Fig. 2 describes the parameterized mass flow diagram of PET beverage bottle. The system starts with amorphous PET resin production and replaced amount of PET resulted from closed loop recycling (=$F_0 - r_{j=1}$). During ISBM, 2.2% of yield loss is assumed to occur. After the ISBM process, 34.212 kg of PET beverage bottles (= F_1) are produced. F_1 (30%) is not collected during PCB collection(= $0.3F_1 = r_{i=1}$), and 70% of F_1 is collected. After PCB collection, some amount of PET bale (36% of F_1) is exported to China. $r_{j=1}$ is used to replace the initial amount of PET resin used within the system boundary, and ($r_{j=2}$)is utilized to reduce the amount of PET resin out of the system boundary resulting in environmental benefit as avoided burden.

To sum up, approximately 70% of F1 is collected through PCB collection, of this amount 36% is exported to China, and 34% is available for the MRF. During the reclamation process 12% is lost. Thus, a total of 22% of F_1 is recycled and re-introduced to the PET beverage bottle system in California. This amount is hypothetically increased by reducing either the PCB collection waste (= $r_{i=1}$) or yield loss of the recycling process(= $r_{i=2}$). So, the total amount of recyclable PET is a sum of 22% of F_1, and a reduction amount of PCB collection waste or yield loss of the recycling process $\left(\sum_{j=1}^{2} r_j = 0.22F_1 + \sum_{i=1}^{2} r_i\right)$. The maximum increase of recyclable PET from PCB collection is 29.6% of F_1, while 12.2% of F_1 is the maximum amount from the yield loss of recycling process.

In order to analyze the effect of theses variables, several scenarios were established as indicated in Table 2 and compared to evaluate the sensitivity of recyclable PET. In base scenario, total 21.73% of F_1 (= 7.27 kg) was assigned to be recyclable PET and converted to environmental benefit. In scenario 'c' the total amount of recyclable PET was hypothetically increased by reducing the PCB collection waste, whereas scenario 'r' is adding up the total amount of it by lowering the yield loss of the recycling process.

2.5. Life cycle impact assessment (LCIA)

The tool for the reduction and assessment of chemical and other environmental impacts (TRACI) was employed for calculating the life cycle impact assessment methods (Bare et al. 2000; Bare et al., 2012). Especially, in this study, a recent version of TRACI, TRACI v2.1, is used. TRACI v2.1 was specifically designed for the U.S. using input parameters consistent with the U.S. locations (Bare et al., 2012). Moreover, TRACI v2.1 is consisted consistent with the existing policies and regulations in the U.S. and provides high versatility in the U.S. market (Bare et al., 2012).

2.6. Interpretation

By definition, interpretation in LCA is "the phase in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope to reach conclusions and recommendations"(ISO, 2006a). Heijungs and Kleijn (Heijungs and Kleijn, 2001) have defined five numerical approaches to life cycle interpretation; contribution analysis, perturbation analysis, uncertainty analysis, comparative analysis and discernibility analysis.

Contribution analysis is used to find the 'hot spot' by decomposing the aggregated results of inventory analysis into a number of constituent elements. For this reason, the model in this study was designed with 5 sections (1. Material production, 2. PET bottle production, 3. Waste management 4. Environmental benefit and 5. Transportation). To assess the variation and the uncertainty of the results, uncertainty analysis was performed using Monte Carlo simulation. Monte Carlo simulation is often used in measuring the uncertainty of complex system by replacing point estimates with random variables drawn from probability density functions (LaGrega et al., 2010). In this study, the standard deviation and probability density function for most of the input parameter was implemented by the data base provider for SimaPro software, and some of it was determined by using a pedigree matrix (Weidema, 1998). In order to apply the statistical comparison for scenario 'c' and 'r', a discernibility analysis was also performed. This analysis stems from the desire to combine the comparative analysis and the uncertainty analysis, which requires a Monte Carlo simulation. Unlike uncertainty analysis, however, this analysis estimates the difference between two products or two scenarios with respect to the selected item, such as the results of the impact indicators or emission.

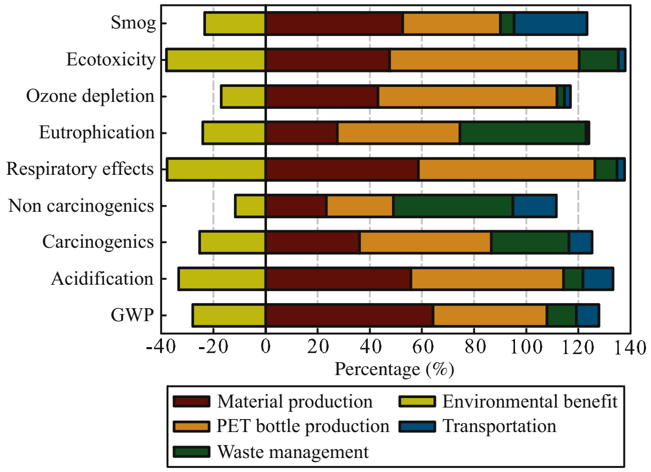

Fig. 3. Results of contribution analysis for scenario S1; results are standardized in percentage value per each life cycle stages. Due to the environmental benefit category's negative values, totals presented can go over 100 percent.

3. Results and discussion

3.1. Contribution and uncertainty analysis of the base scenario

Table 3 explains the uncertainty analysis result for the base scenario. Some of the indicators show high standard deviation, coefficient of variation (CV) and wide 95% confidence interval (CI), such as carcinogenic, non-carcinogenic, eutrophication and ecotoxicity. This is mainly because all these impact indicators reflect on the disposal of various wastes, such as PET, hard coal ash and waste from coal mining, which has high uncertainty on the inventory data. Despite its high uncertainty, results of those impact indicators were considered to have wider environmental insight of this system.

Fig. 3 describes the results of the contribution analysis for the base scenario, which includes 21.73% of F_1 as recyclable PET, equal to 7.27 kg of PET. PET bottle production is the largest contributing section in almost every impact indicator except GWP, eutrophication and smog. Material production, PET bottle production, waste management and transportation sections were contributing the environmental burden, whereas the environmental benefit section reduces the environmental burden as described by a negative percentage.

The highest GWP (120.4 kg CO_2 eq.) and smog (0.20 g NOx eq) was recorded in the material production section. Specifically, production of xylene was the highest contributing inventory process. The second highest section was the PET bottle production (81.9 kg CO_2 eq) and (0.15 g NOx eq), and hard coal combustion for electricity generation was the largest GWP and smog generating inventory process. The recycling and energy recovery from combustion of waste allocated to the environmental benefit section saved 52.3 kg CO_2 eq and 0.093 g NOx eq.

Table 2
Description of the scenario setup based on two different sources (scenario 'c' and scenario 'r') to increase the recyclable PET, variables $r_{i=1}$ and $r_{i=2}$ were defined in Table 1.

Scenario	Scenario code	Variable	Recyclable PET
Base	S1		21.73% of F_1 (7.27 kg)
Scenario 'c'	S2	$r_{i=1}$	21.73% of F_1 + 10% of F_1 from $r_{i=1}$ (7.27 + 3.35 kg)
	S3		21.73% of F_1 + 29.6% of F_1 from $r_{i=1}$(7.27+9.90 kg)
Scenario 'r'	S4	$r_{i=2}$	21.73% of F_1 + 10% of F_1 from $r_{i=2}$ (7.27 + 3.35 kg)
	S5		21.73% of F_1 + 12.2% of F_1 from $r_{i=2}$ (7.27 + 4.08 kg)

Table 3
Results of uncertainty analysis for S1 with coefficient of variance (CV), mean ± standard deviation and 95% confidence interval for each impact indicator.

Impact category	Unit	CV (%)	Total	95% CI
Global warming	kg CO_2 eq	15.2	187.4 ± 28.5	[141,259]
±Acidification	H+ moles eq	22.4	46.80 ± 10.5	[30.6, 72.8]
Carcinogenics	kg benzene eq	109	0.3865 ± 0.421	[0.181, 0.880]
Non-carcinogenics	kg toluene eq $\times 10^{-3}$	207	6.343 ± 13.1	[2.18, 15.2]
Respiratory effects	kg $PM_{2.5}$ eq	33.1	0.215 ± 0.0711	[0.127, 0.396]
Eutrophication	kg N eq	67.8	0.6205 ± 0.421	[0.277, 1.71]
Ozone depletion	kg CFC-11 eq $\times 10^{-6}$	16.9	9.70 ± 1.64	[6.93, 13.3]
Ecotoxicity	kg 2,4-D eq	71.8	281.4 ± 202	[108,685]
Smog	g NOx eq	14.1	0.398 ± 0.0561	[0.309, 0.539]

PET bottle production (27.4H+ moles eq) was the largest contributing section for acidification, specifically due to hard coal combustion during electricity generation. Because electricity generation is a significant inventory process in acidification, the largest environmental benefit was also found in the energy recovery from the incineration of plastic waste to save the amount of hard coal (8.61H+ moles eq.)

Carcinogenic and non-carcinogenic indicators are often significant indicators in terms of disposal of material. For carcinogenic, PET bottle production (0.20 kg benzene eq) was the largest contributing section, and the disposal of uranium tailings and spoil from coal mining for electricity generation was the main inventory processes, whereas in non-carcinogenic, plastic waste dominated the total environmental burden, possessing 66% of total non-carcinogenic impact indicator, specifically landfill of PP and PET. This trend was also found in the results of ecotoxicity and eutrophication impact indicator.

Respiratory effects were mainly interpreted as the effect of air quality change (PM 2.5 level change) on human health. In other words, this indicator is mainly related with air emission, which is mostly generated by combustion of hard coal for electricity generation in PET bottle production process.

PET bottle production (6.65×10^{-6} kg CFC-11 eq) was the largest contributing section during ozone depletion. Specifically, the production of tetrachloroethylene and dichloromethane, used to produce the solvent for injection molding were the most significant inventory process.

3.2. Discernibility analysis

Fig. 4 describes the results of the different scenario comparisons. In order to conveniently analyze the results, three impact indicators were grouped per plot. Each impact indicator shows the results of five hypothetical scenarios, and the total value of the impact indicator is presented at the top of the bar. Detailed discernibility analysis results are available in the Supporting information Table A. 4–13. The results show that scenario S2 reduces 6.5 kg CO_2 eq. of GWP compared to the S1, whereas S3 saves 19.4 kg CO_2 eq. Despite the same increase amount for recyclable PET in both S2 and S4 (10% of F_1), it shows a different GWP saving because the decision made in S2 and S4 affect the supply chain differently.

In Fig. 2, a decision made in scenario S2 will subsequently increase the weight of shipment in T_5 and T_6, amount to be handled in MRF, weight of shipment in T_7 and T_8, yield loss from reclamation process, and amount to be recycled. On the other hand, in scenario S4, it will affect the supply chain by increasing the amount to be recycled only. For this reason, scenario S4 shows more preferable environmental benefit than scenario S2. When it comes to comparing scenarios S3 and S5, because the maximum amount to be able to increase the recyclable PET from S3 (29.6% of F_1) is higher than S5 (12.2% of F_1), S3 shows better environmental benefit than S5 for all impact indicator results.

In order to objectively compare scenarios 'c' and 'r', an additional analysis was conducted by hypothetically reducing 1 kg of PET from yield loss and PCB collection waste as shown in Fig. 5. Aside from this, scenario for 1 kg reduction of PET from F_1 (source reduction) was also compared. One kg reduction of PET from the beginning of life cycle represents the lightweight of PET bottle, which is a major trend in beverage companies. The results show that 1 kg PET reduction in yield loss produces most environmental benefit in GWP, non-carcinogenic, eutrophication and ozone depletion. The main contributing section to differentiate the total GWP impact indicator is the environmental benefit section, which favors more environmental benefit of yield loss reduction than source reduction. In the case of non-carcinogenic, eutrophication and ozone depletion, not only in the environmental benefit section, but also the waste management section plays a major role to generate higher environmental benefit for yield loss reduction than source reduction. Source reduction presented the highest environmental benefit for the rest of the impact indicators.

4. Conclusions

The environmental footprint of the life cycle of non-alcoholic single-serve size PET beverage bottle in the state of California was modeled. Two scenarios besides the current system were established to evaluate the effect of increasing recyclable PET from reducing different PET waste sources; PCB collection waste (scenario 'c') and yield loss from recycling of PET (scenario 'r'). Scenario 'c' suggests a possible environmental benefit by improving the PCB collection system, whereas scenario 'r' may be interpreted as the potential environmental credit generated by improving yield efficiency in the reclamation process.

The contribution and uncertainty analyses revealed that the main environmental burden of the current PET bottle system was contributed by the PET bottle production in acidification (27.4H+ moles eq.), carcinogenic (0.20 kg benzene eq.), non-carcinogenic (1631.7 kg toluene eq.), respiratory effects (0.15 kg

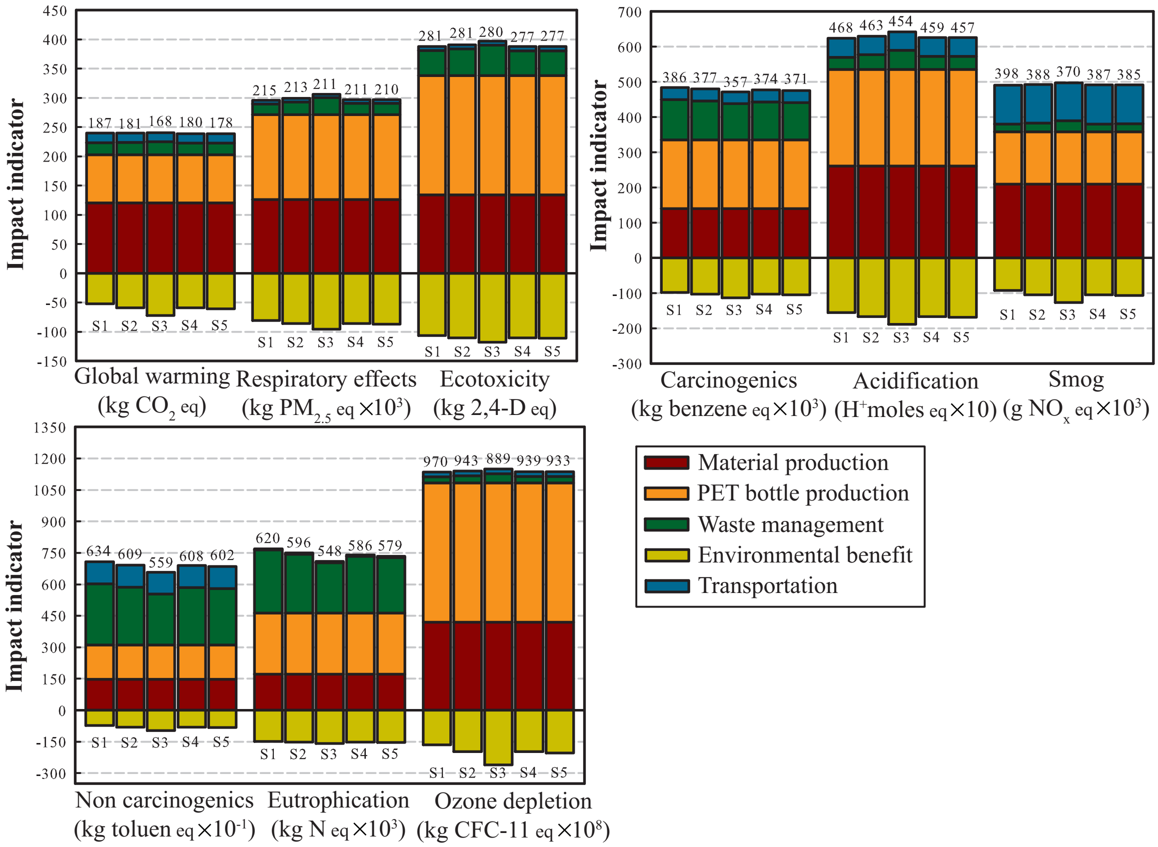

Fig. 4. Results of scenario comparison. Numbers on top of the bars indicate the values of the total impact indicator. The type of impact indicator with its unit is described at the bottom of the plots. Three indicators of different magnitudes were jointly represented per plot to facilitate the discussion of the results.

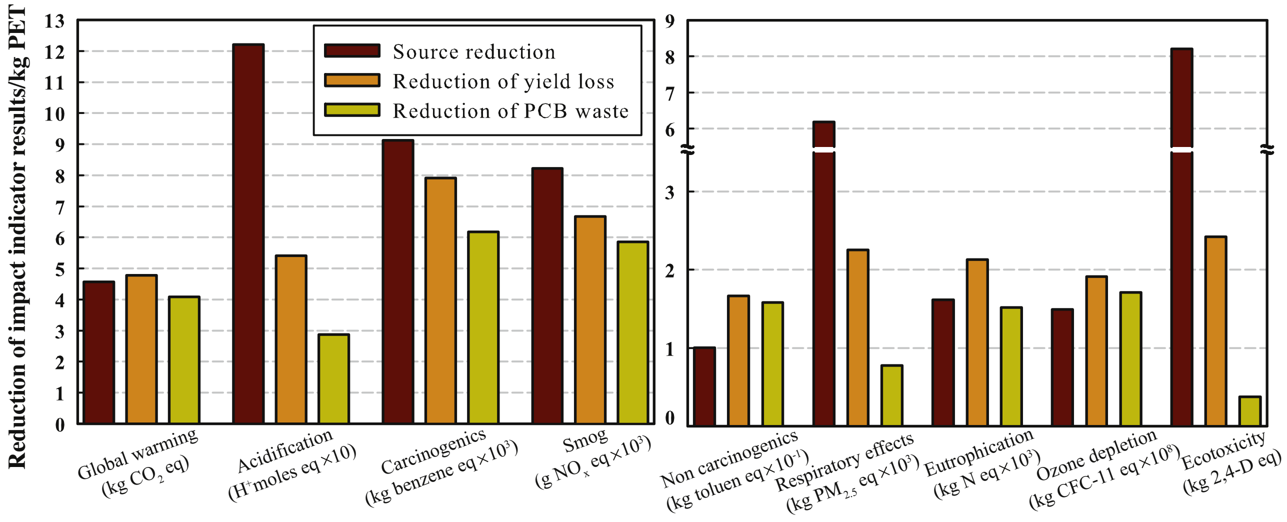

Fig. 5. Comparison of environmental benefit for 1 kg PET reduction of F_1 (source reduction), PCB collection waste and yield loss, type of impact indicator with unit is described at the bottom of plot. Three indicators of different magnitudes were jointly represented per plot to facilitate the discussion of the results.

PM2.5 eq.), ozone depletion (6.65×10^{-6} kg CFC-11 eq.) and ecotoxicity (204.4 kg 2,4-D eq.). The material production section was the main source of GWP (120.4 kg CO_2 eq.), eutrophication (0.17 kg N eq.), and smog (0.20 g NOx eq.).

Discernibility analysis showed that scenario ‘r’ has larger environmental benefit than scenario ‘c’ in every impact indicator. Among the three scenarios, yield loss reduction (scenario ‘r’) has higher environmental benefit than PCB collection waste (scenario ‘c’) and source reduction in reducing GWP, non-carcinogenic, eutrophication and ozone depletion. Source reduction was the best option in terms of acidification, carcinogenic, respiratory effects, ecotoxicity and smog.

Thus, the state of California is considered to be the number one consumption and recycling state for PET beverage bottle in the U.S., representing 70% recycling rate (CalRecycle, 2013). It implies that PCB collection system in the California is well established, resulting in that the possibility to achieve the PCB collection waste reduction may be relatively lower than the yield loss reduction of reclamation process. This conclusion is only based on the results of this study without the consideration in difficulty level of each technology development. This conclusion, however, can help to determine which option needs to be prioritized to manage the environmental burden of non-alcoholic single-serve PET beverage bottle in the state of California, and it can be used as a model for optimizing the recovery of PET bottles in the other 49 U.S. states and around the World.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2016.09.011.

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