Resources, Conservation and Recycling 116 (2017) 45–52

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

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

DongHo Kang[a,b], Rafael Auras[a,*], Jay Singh[c]

[a] School of Packaging, Michigan State University, East Lansing, MI, 48824, United States
[b] Korea Institute of Industrial Technology, Bucheon-si Gyeonggi-do, 421-742, South Korea
[c] Industrial Technology and Packaging, California Polytechnic State University, San Luis Obispo, CA, 93407, United States

ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form 7 September 2016
Accepted 8 September 2016
Available online 17 September 2016

Keywords:
LCA
PET
Environmental performance
Management intervention
Bottles

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.

* Corresponding author.
E-mail address: aurasraf@msu.edu (R. Auras).

http://dx.doi.org/10.1016/j.resconrec.2016.09.011
0921-3449/

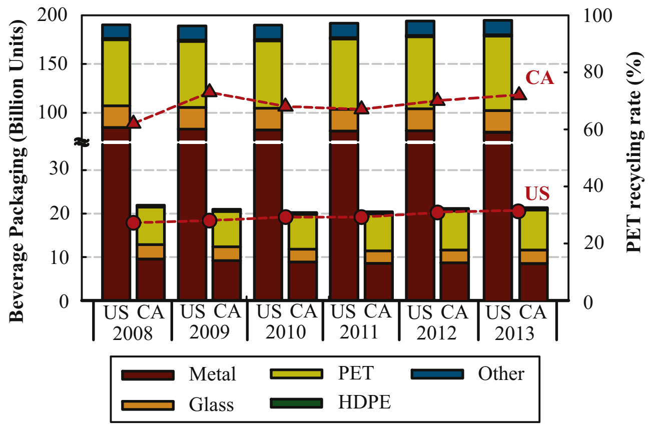

Fig. 1. Beverage packaging market in the US and the state of California; red triangle indicates the recycling rate of PET in the state of California, whereas red round circle indicates the PET recycling rate in the US, data obtained from Ref. (CalRecycle, 2013; Euromonitor International, 2013a; US EPA, 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