ARTICLE IN PRESS

Waste Management xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

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

Life cycle assessment of bottled water: A case study of Green2O products

Naomi Horowitz, Jessica Frago, Dongyan Mu *

School of Environmental and Sustainability Science, Kean University, 1000 Morris Ave., Union, NJ 07083, United States

ARTICLE INFO

Article history:
Received 24 August 2017
Revised 19 January 2018
Accepted 19 February 2018
Available online xxxx

ABSTRACT

This study conducted a full life cycle analysis of bottled water on four types of bottles: ENSO, PLA (corn based), recycled PET, and regular (petroleum based) PET, to discern which bottle material is more beneficial to use in terms of environmental impacts. PET bottles are the conventional bottles used that are not biodegradable and accumulate in landfills. PLA corn based bottles are derived from an organic substance and are degradable under certain environmental conditions. Recycled PET bottles are purified PET bottles that were disposed of and are used in a closed loop system. An ENSO bottle contains a special additive which is designed to help the plastic bottle degrade after disposed of in a landfill. The results showed that of all fourteen impact categories examined, the recycled PET and ENSO bottles were generally better than the PLA and regular PET bottles; however, the ENSO had the highest impacts in the categories of global warming and respiratory organics, and the recycled PET had the highest impact in the eutrophication category. The life cycle stages that were found to have the highest environmental impacts were the bottle manufacturing stage and the bottled water distribution to storage stage. Analysis of the mixed bottle material based on recycled PET resin and regular PET resin was discussed as well, in which key impact categories were identified. The PLA bottle contained extremely low impacts in the carcinogens, respiratory organics and global warming categories, yet it still contained the highest impacts in seven of the fourteen categories. Overall, the results demonstrate that the usage of more sustainable bottles, such as biodegradable ENSO bottles and recycled PET bottles, appears to be a viable option for decreasing impacts of the bottled water industry on the environment.

Published by Elsevier Ltd.

1. Introduction

Bottled water is a fast growing industry, with consumption reaching a record high in 2015 with 11.7 billion gallons (Rodwan, 2016). In 2016 bottled water consumption in Mexico was the highest worldwide with 67.2 gallons per capita, followed by Thailand with 56.9 gallons per capita, Italy with 47.5 gallons per capita, and the United States with 39.3 gallons per capita (Statista, 2017). In 2012, worldwide consumption of bottled water totaled 288 billion liters, while the projected consumption for 2017 totaled 391 billion liters (Statista, 2017). As the industry booms, however, it raises increasing concerns over resource use, human health, and on the negative impacts to ecological systems.

One major concern is the predominant application of plastic bottles made from a petroleum product such as polyethylene terephthalate (PET) (Revathi, et al., 2017). PET is a long-chain polymer part of the polyester family (Sinha, et al., 2010; Muschiolik, 1997). The intermediates of PET are terephthalic acid (TPA) and ethylene glycol (EG) which are both acquired using oil feedstock (Sinha, et al., 2010). Pure PET is a shapeless, glass-like material that crystalizes when certain modifying agents are added or when heat is applied above 72 °C (Sinha, et al., 2010). Typical PET bottle are a major threat to the environment due to the high amount of chemicals, namely petroleum, required in production, as well as incorrect usage and disposal (Revathi, et al., 2017). Approximately 4% of the petroleum used annually in the world in 2016 was for the production of plastic (British Plastic Federation 2016). Bottled water also results in a large amount of waste. According to the study by the Center for Sustainable Systems, University of Michigan (2015), approximately 7.2–14.1 million tons of plastic waste disposed of in landfills each year accounts for 22% to 43% of waste disposed in landfills (Gourmelon, 2015). The majority of plastics are not biodegradeable, and therefore the bulk of the polymers manufactured will persist for decades, centuries, and quite possibly millennia (Hopewell, et al., 2009).

The environmental concerns regarding plastic waste are creating incentives to develop alternatives for petroleum based bottle manufacturing to reduce plastic solid waste disposal (Zia et al., 2007). Currently, scientists have developed many alternatives to

Abbreviations: ENSO, Environmental Solution; GHG, greenhouse gas; GWP, global warming potential; PET, polyethylene terephthalate; PLA, polylactic acid.

* Corresponding author.
E-mail address: dmu@kean.edu (D. Mu).

https://doi.org/10.1016/j.wasman.2018.02.043
0956-053X/Published by Elsevier Ltd.

divert plastic bottles from landfills. Intensive research has been put into the field of recycling. Recycling allows for a closed loop system to repurpose the bottle after disposal. Another alternative is the usage of biodegradable plastic bottles, such as corn-based polylactic acid (PLA) bottles. PLA bottle grade is essentially carbon neutral since it is derived from carbon sequestering plants, and as such is also biodegradable when under appropriate environmental conditions (West, 2016).

Environmental concerns, however, are raised with different options for diverting plastic bottles from landfills. For example, recycling uses energy to sort and process the plastics, which increases the resource consumption and cost. Many water bottle industries hesitate to recycle plastics resin because the cost may be even higher than the new plastic resin (Intagliata, 2012). Similarly, the PLA resin is derived from renewable resources such as, biomass of sugar cane or corn starch (Madival, et al., 2009). Growing raw materials for PLA consumes energy and resources, which increases life cycle impacts of PLA bottles significantly. Another misconception seems to be that PLA will simply degrade once in a landfill, however, the PLA plastic is only compostable under certain environmental conditions – mainly when digested by microbes with temperatures reaching 140 ^{O}F for ten consecutive days (Royte, 2006). In addition, increasing PLA production seems to be a question of morality when so many people in the world are starving and malnourished (Royte, 2006).

The ENSO bottle is a relatively new alternative created to increase biodegradability of plastic bottles in landfills. ENSO bottles are regular PET bottles which contain an additive that makes the bottles more enticing to the billions of microorganisms which normally degrade plastic bottles. The microorganisms break down the bottles into biogases and inert humus leaving no toxic materials behind (ENSO Bottles, 2009). After the ENSO additive is mixed into the plastic bottle components, the final product looks, feels, and performs exactly as a normal bottle would, with the exception of being biodegradable. Research has found that ENSO plastics biodegrade by about 25 percent in only 160 days in ideal environmental conditions (Huff, 2013). In addition, ENSO plastics can be recycled just as any other typical plastic would, however, since a majority of the bottle is composed of petroleum based plastic resin, carbon dioxide (CO_2) and methane (CH_4) are released once the bottle decomposes.

In order to evaluate whether PLA and recycled PET bottles are beneficial for the environment, past research was conducted on the Life Cycle Assessment (LCA) of ordinary PET bottles in conjunction with recycled PET and corn based PLA bottles. A study done by Li Shen et al. (2010), analyzed open loop recycling of PET bottles with four PET recycling cases: mechanical recycling, semi-mechanical recycling, back-to-oligomer recycling, and back-to-monomer recycling. The results were also compared to polylactic acid (PLA) bottles. The results concluded that recycled PET fibers have lower environmental impacts than virgin fiber production, specifically, in the categories of abiotic depletion, acidification and human toxicity. The recycled fibers were found to have a comparatively high environmental impact on freshwater aquatic ecotoxicity than the virgin PET, as well as a lower Global Warming Potential (GWP), than PLA bottles. While Li Shen et al. conducted a LCA study on recycled PET and PLA bottles, no LCA study has been conducted on ENSO bottles in conjunction with regular PET, recycled PET, and PLA bottles.

This study analyzed three supposed environmentally friendly bottle alternatives: recycled PET bottles, PLA bottles and ENSO bottles. As a baseline, the regular petroleum based PET bottles were analyzed for comparison. The study coordinated with the bottled water manufacturing company Green2O, a New Jersey based water bottle company that aims to provide a premium all natural alkaline spring water, packaged in an environmentally conscious container. The company proposed three product lines with different bottle vendors to produce bottled water. Therefore, this study developed a model that integrated the bottle manufacturing, water fillers, and product distribution in a Green2O scenario. The study also aimed to identify the key production stages that raise environmental impacts in the bottled water production.

The outcomes of this study are expected to increase the public's understanding of environmental impacts of plastic bottles and enlighten the water bottle industries of the impacts of various plastic bottle alternatives. The results can also help the bottle manufacturing industries improve their products to lower environmental impacts in certain production stages.

2. Methodology

The framework of this study followed the guidelines according to ISO 14,000 standards for LCA. Data applied in LCA modeling and analysis were either collected from the Green2O product chains or retrieved from existing LCA databases, such as EcoInvent 3.1. A scenario analysis was also conducted in order to determine if combining various percentages of recycled PET resin and regular PET resin would have a lower impact on the environment.

2.1. Goal and scope

The goal of this project was to analyze the environmental impacts of Green2O bottles by assessing 4 types of plastic materials including ENSO, PLA, 100% recycled PET, and regular PET. The 100% recycled PET bottle was assumed entirely made from recycled plastic resin. The PLA bottle was assumed to be corn based and compostable. The ENSO bottle consists of regular PET resin, albeit contains a special additive (1% by weight), which allows it to degrade in a landfill extremely quickly. The regular PET was assumed to be petroleum based plastic material. The functional unit denoted for this project was 12 bottles, as this amount is typically found in one pack of Green2O water bottles.

The system boundary for the bottles being studied is illustrated in the flow diagram in Fig. 1. The boundary took into account the complete life-cycle, beginning from the extraction of raw materials through the disposal of the product in a landfill. This boundary included plastic material manufacturing, bottle manufacturing, filling the bottles with water, assembly of the product, distribution of the product to storage and the market, consumption, and disposal/recycling. Generally, the bottle preforms were assumed to be made of different raw materials at different locations, and then transported to Tennessee to be filled with water. The bottle manufacturing is described in Fig. 1. The products, bottled water were then distributed across the country. This study assumed identical distribution and use stages for the four types of water bottles. The final disposals of four types of bottles were different and described in Fig. 1 as well.

2.2. Life cycle Inventory (LCI)

The goal of Life Cycle Inventory (LCI) was established to identify and quantify the environmental factors crossing the system boundaries. LCI data, as shown in Table 1, consisted of raw material and energy inputs utilized to create each product. The LCI included all the unit processes and quantity of inputs shown in Fig. 1. The impacts of unit processes such as plastic resin production, blow molding, and water injection were attained from Ecoinvent 3.0 database on Simapro. The material use and inputs were based on the actual weight of bottles and packaging. All the calculations used to derive the quantitative data are described in the Supplementary Information (SI).