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Circular economy of expanded polystyrene container production: Environmental benefits of household waste recycling considering renewable energies

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Abstract

Plastic industry is ubiquitous worldwide, and the generation of "plastic waste" has been steadily increasing to the point of being considered a high impact pollutant. The expanded polystyrene (EPS) plastic industry aware of the issue is interested on trying recycling post-consumer material. Through a recent study made in an alliance between the private sector and the academy, the feasibility of the EPS "mechanical" recycling was proven; therefore, a possible solution through a circular economy model. The aim of the present paper was to investigate the potential environmental impacts avoided by the circular economy scenario previously developed, through a life cycle assessment (LCA) performed for the city of Guayaquil, where 64% of all the plastic manufacturing industries in the country are located. The entire life cycle of 1.00 kg of 5 × 5 inch. food containers were assessed from the production stage until its end-of-life stage: focusing on three different valorization paths, circular economy closed-loop (container-to-container) proposal with electricity share of 2019 and another with the 2027 future one, and traditional linear economy (container-to-landfill). Results showed that the scenario C that considers the recycling of post-consumer EPS waste and the electricity share proposed for 2027 have lower impacts in 14 out of 16 categories, in specific for the Land use (−31%), Ozone Depletion (−28%), Acidification (−24%) and Terrestrial and Marine Eutrophication (−21%). These results strongly suggest that the recycling of these kind of plastic waste could benefit the environment greatly.

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Keywords: Recycling; Single-use plastics; Expanded polystyrene (EPS) waste; Circular economy; Life cycle assessment (LCA); Renewables

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1. Introduction

Waste management is a rising global issue which is not only expensive but also environmentally damaging. Nowadays, a significant contributor to the waste stream is single-use plastic containers, used for carry-out food at public and private institutions, residences, and retailers. Plastic waste is internationally recognized as a problem; indeed, the raising public awareness of environmental concerns have resulted in the implementation of public policies banning its waste imports. In this context, expanded polystyrene (EPS), is among the most commonly used containers for carrying-out food due to its excellent properties, i.e., light weight, rigidity, good insulation properties and high impact resistance [1]. The mass of EPS in carrying-out containers is rather less, about 2%, corresponding most of its weight, about 98%, to air. Polystyrene is cataloged as a Type 6 polymer according to the society of plastics industry (SPI) [2]. In 2016, the global production of polystyrene and expanded polystyrene was around 14.7 and 6.6 million metric tons (MMT) per year, respectively (grandviewresearch, 2017).

Regrettably, the fate of EPS post-consumer container products is the city landfill, generating a significant amount of waste and becoming an environmental burden, as well as most plastics require a long-time to degrade under environmental conditions (up to several hundred years) (3; Moreira et al. 2016; Acosta et al. 2017). Importantly, during the last decade Polystyrene (PS) share is around 10% wt. of the universe of plastic waste [4], being one post-consumer waste product of greatest concern due to its poor recycling rates [5]. The per capita daily solid waste generation rate for the city of Guayaquil is 0.58 kg [6], from which, 9.50% corresponds to plastic waste [7]. From this waste, expanded polystyrene represents 5.25% of all the plastic waste [8]. Considering a total of 2.291 million people living in the city, for the year 2010 according to the last Census performed by the National Institute of Statistics and Censuses (INEC), we can predict that at least 6.63 tons of solid domestic EPS waste ends up in the local landfill every day.

The environmental challenges due to the consumption of single-use plastics have increasingly come to the attention of politics and legislation in Ecuador, leading to the release of the Organic Law for the Rationalization, Reuse and Reduction of Single-use Plastics on December 21st, 2020. The approved law seeks to regulate the generation of plastic waste the progressive reduction of single-use plastics through responsible use and consumption, the reuse and recycling of waste and, when possible, its replacement by packaging and products made with recycled material or biodegradable with a lower carbon footprint than the everyday used product, to contribute to health care and the environment (Third Supplement of Official Gazette No. 354 of December 21, 2020). The authors through a case study in 2019 showed that is possible the recycling of EPS post-consumer waste and developed a circular economy proposal using 40% of virgin resin, 30% of scrap recycling resin from the production process and 30% post-consumer recycled resin, new EPS 5 $\times$ 5 in. containers were obtained with the same quality as the traditional 70% virgin resin and 30% scrap recycling resin [9].

Ecuador's electric power system has a net capacity of nearly 8200 MW. Over 60% of this capacity is hydropower, approximately one-third of the capacity is fossil-fuel fired, and the remaining 2% comes from non-hydro renewables (biomass, biogas, wind, and solar). However, for 2019, Ecuador's electricity inputs came from fossil-fuels in their majority with almost 52%, followed by hydropower with 46%, and other renewables with almost 2.50%. Additionally, the industry (39%), residential (29%), and commercial (27%) sectors account for 95% of all electricity usage. Ecuador anticipates a 7% average annual growth in electricity demand through 2027, with demand reaching a total of 44,715 GWh in 2027 (before considering recent economic impacts of COVID-19). In the electricity sector, Ecuador lacks substantial development of non-hydro renewables, namely solar, wind, biogas, biomass, and geothermal systems. By 2028, MERNNR (2020) projects that non-hydro renewables will make up less than 5% of installed capacity in the country. The latest planning documents indicate that Ecuador plans to add 5300 MW of capacity by 2027. Most of this capacity (80%) will be hydropower, 10% thermoelectric, and 10% non-conventional renewable energy. (PBYA MACINTYRE, 2020). The electricity source share best case scenario evolution, passing from a total of 48% of renewable energies to 73%, taking into consideration the actual and future installed capacity for each type of source with 68% hydraulic, 27% fossil-fuels 4% biomass and 1% wind/solar.

During the latest years, the demand for studying the environmental impacts of products and systems has continuously increased, being the Life Cycle Assessment methodology the most preferred by researchers. LCA serves as powerful tool to quantify environmental impacts and determine the potential management strategies to reduce those impacts [10]. It supports innovation and technology managers, product designers and engineers by analyzing the consequences of their ideas and decisions with regards to both, the vision of circular economy and the actual consequences for current life cycle systems [11]. It is in fact defined as the compilation and evaluation of the inputs, outputs and of the potential environmental impacts in terms of human health, climate change, resources, and ecosystem's quality, due to a product-systems throughout its life cycle [12]. Following the steps of Gallego-Schmid et al. [13], and Valentino et al. (2016), an LCA study consists of four phases: 1. Goal and Scope, 2. Life Cycle Inventory (LCI), 3. Life Cycle Impact Assessment (LCIA), and 4. Interpretation.

Consequently, the aim of this work is to research the potential environmental impacts avoided by the integration of the proposed EPS circular economy model plus the change in the energy mix for 2027, to the actual city's collection system and energy mix, choosing as an example 5 × 5 in. food containers. For this purpose, in Section 2, the case study is developed to compare the three different scenarios: (a) actual linear economy (container-to-landfill) scenario with current electricity mix; (b) closed-loop recycling (container-to-container) with actual electricity mix; and (c) closed-loop recycling with 2027 best electricity mix scenario, and their environmental impacts results are then shown in Section 3 with discussion. Finally, conclusions are presented in Section 4.

2. Case study design

For this study, the ILCD 2011 Midpoint characterization method released by the European Commission Joint Research Centre in 2011 will be used later during the implementation of the LCA. It includes 16 impact categories listed below:

- Climate Change **(kg CO2 eq)**
- Ozone Depletion **(kg CFC-11 eq)**
- Human Toxicity; non-cancer effects **(CTUh)**
- Human Toxicity; cancer effects **(CTUh)**
- Particulate Matter **(kg PM2.5 eq)**
- Ionizing Radiation for Human Health **(CTUe)**
- Ionizing Radiation for Ecosystems **(CTUe)**
- Photochemical Ozone Formation **(kg NMVOC eq)**
- Acidification **(molc H+ eq)**
- Terrestrial Eutrophication **(molc N eq)**
- Fresh Water Eutrophication **(kg P eq)**
- Marine Eutrophication **(kg P eq)**
- Freshwater Ecotoxicity **(CTUe)**
- Land Use **(kg C deficit)**
- Water Resource Depletion **(m^3 water eq)**
- Mineral, Fossil & Renewable Resource Depletion **(kg Sb eq)**

2.1. Goal and scope

The aim of this work is to analyze the potential environmental impacts generated by EPS food container through their entire life, comparing three different end-of-life scenarios (closed loop recycling with current and proposed electricity mix, and landfill end-of-life) for the context of the city of Guayaquil, Ecuador. The functional unit considered is 1.00 kg of 5 × 5 inch. with an average weight of 5.00 grams EPS food containers in Guayaquil, Ecuador, meaning that 200 food containers are needed to fulfill the total weight. The entire life cycle of the EPS food container is assessed, from the production stage until its end-of-life stage.

2.2. System description and boundary:

The following life stages are included in the system boundaries: virgin PS production, container production, collection, and sorting phase, and as end-of-life, the recycling treatment, and landfill destination, with the related efficiencies (Y = Yield), followed by the secondary production phase. To track the path of the initial 1.00 kg of EPS takeout food containers produced, a Material Flow Analysis (MFA) is conducted as shown in Fig. 1. Following the structure of the mass flow analysis (MFA), the initial 1.00 kg of EPS food containers in the city context is shown for the three scenarios. As can be seen, after the second loop, the process remains stationary, meaning that there are no variations regarding the amount of virgin PS resin needed and the quantity of waste moved to landfills for both scenarios. The post-consumer recycling process (individual collection, EPS waste reseller and waste reprocess) is considered done by informal waste pickers, that go through household's waste and collect the EPS waste with many other recyclables. After, they transport the waste to the waste resellers who sort and prewash the waste. Finally, the former group provides the sorted and prewashed waste to the waste reprocess companies that will transform the EPS into recycled resin. With respect to the scrap recycling, it is considered equal for all scenarios. The container production uses only to the PS resin and there are not considered any additional materials necessary to produce the food container such as nucleating and foaming agents. The reason behind these exclusions is that these additions

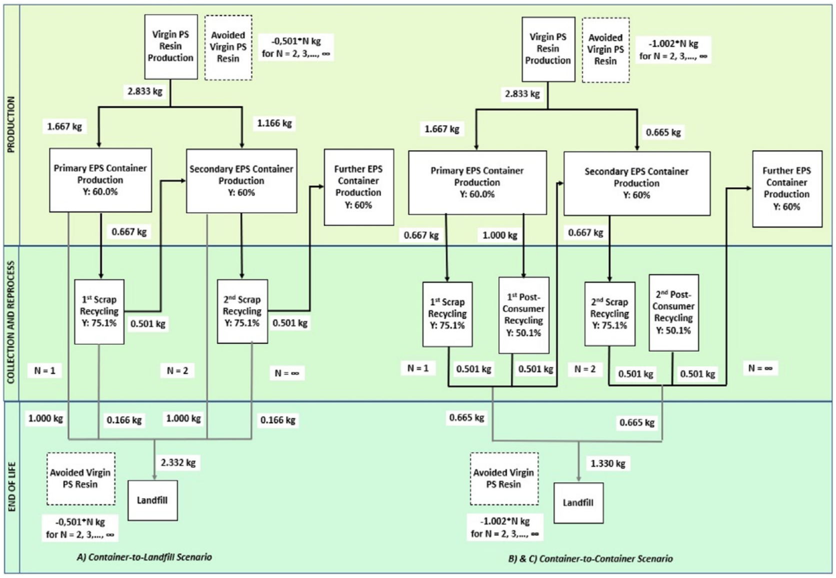

Fig. 1. System boundary and material flow analysis for all three scenarios.

can be considered negligible with respect to the PS resin. Within the container-to-container scenarios, the following production of containers have the restriction of 60% of scrap and post-consumer recycled resin (30% each) hence, it is necessary the use of virgin PS to produce the second and third loop containers. Electricity share values for 2019 and 2027 perspectives written in Section 1, are used for the two closed loop scenarios.

2.3. Inventory analysis:

This phase is necessary to quantify all the materials, resources and emissions associated to the life stages as shown in Fig. 1. Each stage has been modeled using the software SimaPro 9.1, that permits to analyze and model life cycles of goods and services while measuring their environmental impacts.

(a) Production stage: For the primary material production (i.e., PS granules) the Polystyrene granulate (PS)/EU-27 from the Eco-invent database. An efficiency of 100% is here assumed. This phase also accounts to produce 1.00 kg of EPS 5 × 5 in. food containers, in accordance with the goal and scope definition. The 4000 miles transport by transoceanic tanker of the virgin PS from the American manufacturer to the port of Guayaquil, after the thermoforming in line of plastic sheet, and finally, the thermoforming of the plastic sheet into food container. The related datasets used were: (1) Extrusion of plastic sheets and thermoforming, inline {RoW} processing / Conseq, S, (2) Thermoforming of plastic sheets {FR} / processing / Conseq, S, and (3) Transport, freight, sea, transoceanic tanker {GLO} processing/ APOS, U. It is considered an efficiency of 60% for the container production. Electricity use for extrusion of plastic sheets is of 0.3412 kWh/kg of finished sheet, also for the thermoforming, it is 0.5445 kWh per kg of finished container. Additionally, LPG used is of 0.05 kg/kg of finished container.

(a) Collection and reprocess stage: For the scrap recycling process we consider a Yield of 75.1%, meaning that from the 40% scrap residue from the production of EPS food container, only 75.1% is processed into scrap recycled resin. Only the process of pellet extrusion is considered in this section with an electricity use of 0.2567 kWh/kg of postindustrial recycled (Extrusion, co-extrusion {GLO} market for / Cut-off, S). For the post-consumer recycling process, we consider a total Yield of 50.10%, meaning that from the 1.00 kg of product, only 0.50 kg are turned into post-consumer resin pellets. The inputs here considered are water, detergent, and the electricity for the pellet production through extrusion. The related datasets used were: (1) 0.004 m3/kg of finished container Tap water {CA-QC} / market for / Conseq, S, (2) 83.33 ml/kg of washed and dried postconsumer recycled product Carboxymethyl cellulose, powder {GLO} / market for / Conseq, S and (3) 0.3462 kWh/kg of recycled postconsumer resin (washing + drying + extrusion) Extrusion,

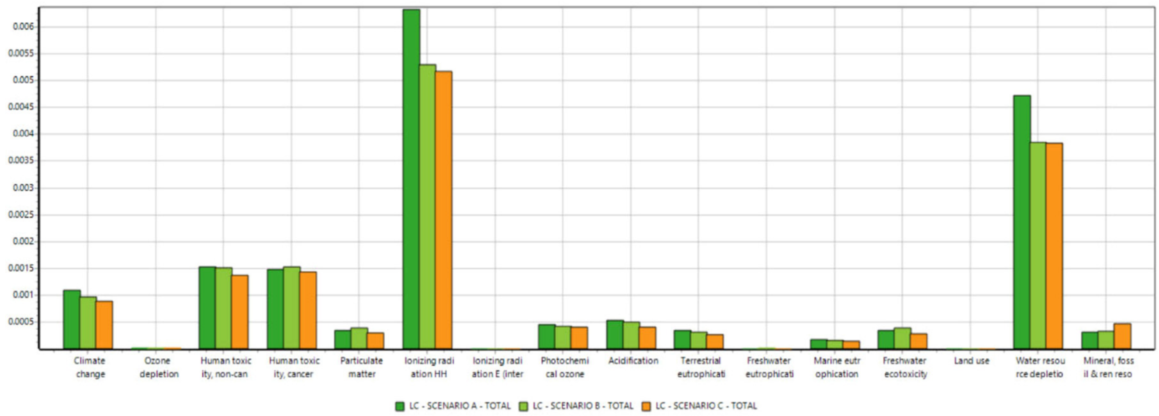

Fig. 2. Normalized impact assessment for each proposed scenario.

co-extrusion {GLO} market for / Cut-off, S. Also, 50 km transportation by truck from the EPS Waste Reseller to the Waste Reprocess Plant is considered here. An additional value for transport is considered here for the movement of the recycled post-consumer pellets to the manufacturer (Transport, combination truck, diesel powered/US).

(b) End of life stage: For the waste disposal, we considered all not recycled material to end up in the local landfill. For this purpose, we used the Municipal solid waste (waste scenario) {RoW} / Treatment of municipal solid waste, landfill / Conseq, S), and the same transport database for the movement of waste to the landfill by the garbage trucks.

3. Results and discussion

Fig. 2 shows the normalized impact assessment of the 16 impact categories included in ILCD 2011 Midpoint characterization. Scenario C with the 2027 electricity mix presents the best-case scenario, better than Scenario b which also accounts for the post-consumer recycled resin. The results obtained through the Life Cycle Impact Analysis (LCIA) method, suggests that the scenario B has lower impacts with respect to scenario A in several impact categories (namely 9 out of 16), but scenario C presents a higher number of lower impacts than Scenario A (namely 14 out of 16). In specific, the best reductions for scenario C, when compared to scenario A are: Land use (−31%), Ozone Depletion (−28%), Acidification (−24%) and Terrestrial and Marine Eutrophication (−21%). However, the effect of washing and drying the post-consumer waste and the use of detergent affects the Freshwater Eutrophication, augmenting this impact in 40%. Additional research indicates that EPS single-use containers create the lowest global warming impact when landfilled compared to polyethylene terephthalate and polylactic acid (Leejarkpai et al. 2016). Therefore, these results strongly suggest that the recycling of these kind of plastic waste, could benefit the environment greatly. However, a sensible restriction to implement the circular economy model proposal is the lack of plastic recycling infrastructure in the city. The analysis of the selective collection of these types of waste is mandatory to plan future policies and actions towards the circular economy. One possible solution is passing legislature supporting small scale plastic sorting and recycling systems within densely populated urban cities; however, this involves that government, private industry, and citizens merge in a common decision; very complicated in any big city.

4. Conclusions

The potential environmental impacts avoided by the implementation of a circular economy model was developed. Software Simapro 9.1 was used for the LCA implementation and the ILCD 2011 Midpoint characterization method to obtain the impacts of three scenarios. Results showed that scenario C that considers the recycling of post-consumer EPS waste and the electricity share proposed for 2027 have lower impacts in 14 out of 16 categories, in specific for the Land use (−31%), Ozone Depletion (−28%), Acidification (−24%) and Terrestrial and Marine Eutrophication (−21%). The solid results reached in this preliminary analysis propose a valid alternative in the single use plastic waste management that future research endeavors may validate applying the LCA methodology.

CRediT authorship contribution statement

J. Hidalgo-Crespo: Investigation, Formal analysis, Validation, Writing – original draft. **C.M. Moreira:** Writing – review & editing. **F.X. Jervis:** Data curation, Writing – review & editing. **M. Soto:** Conceptualization, Supervision, Writing – review & editing. **J.L. Amaya:** Conceptualization, Supervision, Writing – review & editing. **L. Banguera:** Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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