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Carbon and water footprint for the recycling process of expanded polystyrene (EPS) post-consumer waste.

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Abstract

Plastic pollution of the natural environment is ubiquitous, and around 40% of all plastic waste produced globally is used in single-use products and only 9% is recycled. From this plastic waste, expandable polystyrene single-use products pose a major problem because of its great volume and low density. To abord this issue, the authors proposed a circular economy model for EPS post-consumer waste in 2019 through a case study with the help of one local plastic manufacturer. Although the idea of promoting circularity of this waste seems a priori to have a good impact on the environment, the process to reincorporate reused and/or recycled materials under the concept of CE have economic and environmental impacts on the environment that should be measured. To understand if a recycling process is truly beneficial to the environment, first we need to do a sustainability analysis, using sustainability indicators, such as Carbon Footprint (CF) and Water Footprint (WF). The objective of the present paper is to perform a sustainability analysis of the expandable polystyrene post-consumer recycling into resin pellets using CF and WF as sustainability indicators. We proposed three case scenarios considering an artisanal recycling with 2019 (A), and 2027 proposed electricity power mix (B), industrial recycling with current 2019 electricity power mix (C) and the use of virgin PS and its destination in landfill to compare. We measured the CO_2 emissions and m^3 of freshwater with the help of SimaPro 9.1 software. Overall, the total CO_2 emissions for the case scenarios A and B are approximately 42% and 16% higher than scenario D, but scenario C exhibits a reduction of almost 50%. For the water depletion, scenarios A and B show very higher values than those of scenario D with 536% and 534%, respectively. Important to mention that scenario B presents much better values for CF than scenario A, meaning that the increase in the share of electricity production by renewable energies can improve the sustainable production of recycled PS resin.

Keywords: Circular Economy, EPS, Post-Consumer, Waste, Carbon Footprint, Water Footprint

1. Introduction

The search for sustainability has pointed out the need to shift from our linear economy paradigm. The linear and waste-producing value chain problems are solved making them circular. On the one hand, waste generation is reduced by its use as raw materials, and on the other, the non-efficient consumption of natural resources decreases [1]. Nevertheless, such a transition is not trivial, and to achieve this purpose, first it is necessary to modify our current production chains, focusing on reducing the amount of demanded virgin raw materials, cutting emissions, and preventing waste generation. In this context, circular economy (CE) is becoming an important strategy when facing global challenges such as waste generation and resource scarcity.

CE defines and identifies the circularity of materials, components, and products through waste management processes: prevention, reuse, preparation, recycling, other recovery, and final disposition [2]. It is necessary to consider sustainability criteria such as climate change, energy consumption, users' waste generation, and the improvement of

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the processes in manufacturing products and their recycling process [1].

Plastic pollution of the natural environment worldwide is ubiquitous. In 2018, 359 million tonnes of plastic were produced worldwide [3]. Around 40% of all plastic waste produced globally is used in single-use packaging; a little more than 9% is recycled, 12% incinerated, and 79% is disposed into landfills or the natural environment [4]. More than 80% of marine litter is made of plastics, 70% of which originates from disposable items [5].

From this waste, Polystyrene (PS), especially in its expanded form (EPS), is a thermoplastic polymer produced from styrene, a petroleum-derived liquid hydrocarbon, and one of the most used containers for carrying out food due to its excellent properties, i.e., lightweight, rigidity, good insulation properties and high impact resistance [6]. In 2018, one study showed that the per capita daily solid waste generation rate for the city of Guayaquil was 0.58 kg [7], from which 9.50 % corresponded to plastic waste [8], and from this percentage, expanded polystyrene represented 5.25% [9]. 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), it is possible to 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 Organic Law for the Rationalisation, Reuse and Reduction of Single-use Plastics on December 21st, 2020. The approved law seeks to regulate the generation of plastic waste, and the progressive reduction of single-use plastics, through responsible use and consumption, their reuse and recycling and, when possible, its replacement by other recycled or biodegradable materials, with lower carbon footprints [10].

Through a case study in 2019, the authors presented a proposal for the recycling process of EPS post-consumer waste to achieve CE [11]. In this article, an artisanal process for obtaining recycled post-consumer EPS resin was developed with the participation of one of the largest plastic manufacturers in the country. The recycling process consisted of the following stages: (1) collection and sorting, (2) prewashing, (3) washing, (4) drying, and (5) grinding, extrusion and pelletising. However, this process was meant to prove that recycling of this waste was possible, rather than looking for high efficiency. In fact, all the equipments used for the washing and drying were not meant for big scale production, taking 45 minutes per batch of 600 grams of EPS post-consumer waste processed.

Although circular systems promote sustainability, it does not assure environmental benefits since the processes to reincorporate reused and recycled materials to the production chains under the concept of CE have indeed their own economic and environmental impacts. Additionally, the effects of CE on sustainable development are not entirely known; since the flow of other non-material resources such as water, soil, and energy are usually briefly or not at all considered.

To understand if the recycling process is favourable to the environment, it is necessary to develop a sustainability analysis; using sustainability indicators such as Carbon Footprint (CF) and Water Footprint (WF). Both indicators are intrinsically related to the life cycle thinking concept and can be used by companies as indicators of sustainability.

On one hand, CF has become present in the current political and corporate agendas with ramifications in the international trade relations of goods and services [12]. It assesses the total balance of emissions and sinks of Greenhouse Gases (GHG) from a product, service, or system across its life cycle [13]. It accounts for all inputs and processes within a defined system boundary.

On the other hand, WF measures the total volume of fresh water used to manufacture a product throughout the whole production process [14]. It measures the direct use of freshwater by the producer or consumer and indirect uses during the whole life cycle of the product or process [15]. It accounts for the volume of used surface and ground water, related to the use of rainwater, and when rainwater is drained into sewers and contaminated with sludge.

A significant component of cradle-to-resin WF and CF for plastic derives from the fossil-fueld electricity to power production processes. Such processes may be outperformed with renewable or low-carbon energy sources, reducing the carbon intensity of one stage in the plastic recycling process.

The objective of the present paper is to perform a sustainability analysis of the expandable polystyrene post-consumer waste recycling into post-consumer resin pellets using Carbon and Water Footprint as sustainability indicators. through the presentation of three different recycling scenarios.

The rest of this paper is presented as follows. Section 2 shows the materials and methods undertaken to calculate the CF and WF, the case study scenarios and the data used for the calculations. Section 3 presents the case study design, following the life cycle assessment (LCA) methodology and defines the system boundaries and the inventory values from the Ecoinvent database used. Section four presents the results of the WF and CF for four scenarios planted, and discusses the work. Finally, section 5 concludes and sets future perspectives.

2. Materials and methods

This study aims to systematically estimate CO_2 emissions and m^3 of water use for three proposed recycling scenarios of plastic EPS post-consumer waste into recycled resin pellets and compare them to virgin resin and its disposal in the landfill.

- ***Scenario A:*** Artisanal recycling from 2019 case study with 2019 electricity mix.
- ***Scenario B:*** Artisanal recycling from 2019 case study with a proposed 2027 electricity mix.
- ***Scenario C*: **Post-consumer EPS waste industrial recycling with 2019 electricity mix.

The comparison of scenarios A and B will donate insights on the benefits of shifting the countrie´s current energy mix to a more sustainable one. Scenario C instead, analyses how making recycling of EPS post-consumer waste from an industrial point of view can diminish the CF and WF when compared to an artisanl process.

2.1. Electricity mix scenarios

Ecuador's electric power system has a net capacity of nearly 8,200 MW. Over 60% of this capacity is hydropower, and approximately one-third of the capacity is fossil-fuel-fired. By 2019, from the total electricity produced, only 46% came from hydro, and 52% from fossil-fuels. The remaining 2% came from non-hydro renewables (biomass, biogas, wind, and solar).

The latest planning documents indicate that Ecuador plans to add 5,300 MW of capacity by 2027. Most of this capacity (80%) will be hydropower, 10% thermoelectric, and 10% non-conventional renewable energy [16]. The electricity source share best case scenario evolution, passing from 48% of renewable energies to 73%, considering the actual and future installed capacity for each type of energy source is also shown in Figure 1.

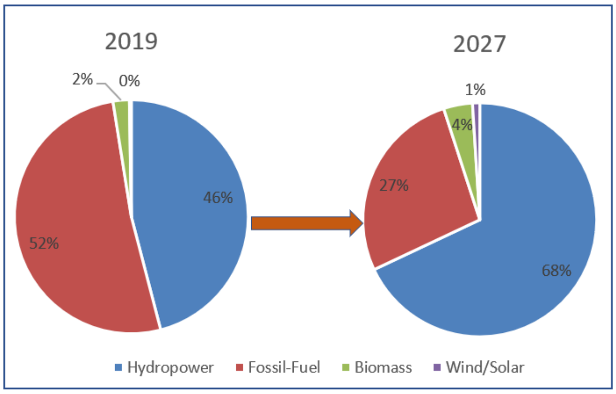

Figure 1. Electricity share best case scenario evolution from 2019 to 2027

2.2. Carbon footprint

The CF measures the total amount of carbon dioxide emissions, CO_2 or CO_2 equivalent, that is directly or indirectly caused by a product, service or accumulated during the life cycle of the product activities. Commonly observed greenhouse gases (GHG) are CO_2, CH_4, N_2O, HFCs, PFCs and SF_6. Among them, CO_2 is the GHG that affects global climate the most. Following the IPCC Inventory Guidelines for Global Warming Potential (GWP), the GWP of CO_2 is set to a standard value of 1, and the GWP of the other GHG are obtained. The UNE-EN ISO 14064-1:2012 standard explains in detail how the GHG emissions inventory must be carried out and its rating in the following scopes [17]:

- Scope 1: Direct emissions occur from sources that are owned or controlled by the company.
- Scope 2: These are indirect emissions generated by electricity acquired and consumed by the organisation.
- Scope 3: These are other indirect emissions that are a consequence of the company activities but occur in sources that are not owned or controlled by the company.

2.3. Water footprint

Evaluation of WF is one of the newest methods for determining the environmental impacts of products or technology. It serves to measure the amount of water required to manufacture various products (m^3 or m^3/kg). Following the methodology of Hoekstra et al. [18], the complete evaluation of WF includes four key steps:

- Establishing of goals and scope of analysis,
- Accounting of water footprint,
- Assessment of water footprint sustainability,
- Formulation of water footprint response.

2.4. LCA and its relationship with CF and WF

LCA serves as a powerful tool to quantify environmental impacts and determine the potential management strategies to reduce those impacts [19]. It supports innovation and technology managers, product designers, and engineers by analysing the consequences of their ideas and decisions regarding the vision of the circular economy and the actual consequences for current life cycle systems [20]. It is defined as the compilation and evaluation of the inputs, outputs, and potential environmental impacts in terms of human health, climate change, resources, and ecosystem's quality, due to a product-systems throughout its life cycle [21].

Following the steps of two previous studies [22-23], an LCA study consists of four phases:

- Goal and Scope: This forms the basis and scope of the subject or product of interest.
- Life Cycle Inventory (LCI): This involves collecting and analysing a well-defined system's relevant or main inputs and outputs.
- Life Cycle Impact Assessment (LCIA): In this step, air and water emissions and raw material and energy consumption are translated into environmental effects.
- Interpretation: Conclusions are drawn from the LCA results, and areas for improvement are identified.

3. Case study design

The case study method is used to illustrate the problem through one or more selected cases, using collected data to examine the logical relations between events. Multiple case studies help provide a more comprehensive understanding and reflect the different aspects of cases, making the approach a more rigorous, scientific, and theoretically validated research model [20].

3.1. Goal and scope

The functional unit considered for this study is the production of 13.5 kg of post-consumer recycled resin. The CF and WF for the entire life cycle of the transformation process from EPS post-consumer waste containers to recycled resin pellets are compared for the three proposed case scenarios. Finally all these scenarios are also compared to the same quantity of virgin raw material transported to the city, in addition to the avoidance of waste reaching the local landill.

3.2 System Description and boundary:

The following life stages are included in the system boundaries: Waste Extraction, Waste Processing, and Waste Trasnformation, as shown in Figure 2.

For Scenarios A and B, we considered the collection of post-consumer EPS waste made by 100 students from two different universities of Guayaquil. However, for scenario C, we considered the recycling process proposed by the authors [11], where informal recyclers or waste pickers go through kurbside trash and collect the EPS residues with many other recyclables. After, they transport them to the bigger waste resellers who sort the waste.

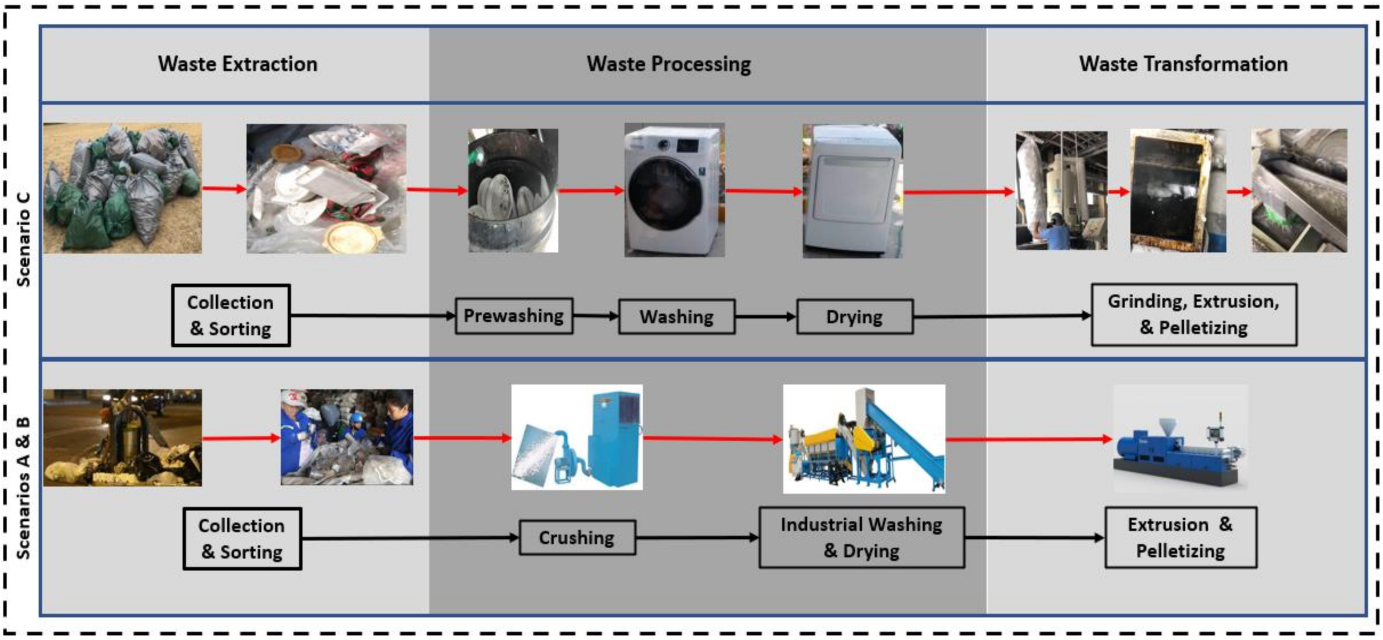

Figure 2. The system boundary of the four case studies

Finally, the former group provides the sorted waste to the reprocess third companies that take care of the waste transformation into resin pellets.

3.3 Inventory Analysis

This phase is necessary to quantify all the materials, resources and emissions associated with the life stages considered in the system shown in Figure 2. Each stage has been modelled using the software Simapro 9.1, which permits analysing and modelling the life cycles of goods and services while measuring their environmental impacts, using the ECOINVENT database.

Scenario A: For the waste extraction, a total of 150 students participated and gathered a total of 230 kg. Then an average of 1.50 kg/ student is considered here. Each student is expected to travel an average of 10 km from their household to the gathering point. We considered that 50% traveled by diesel-powered bus and the rest by gasoline-powered cars. As said before, the functional unit is 13.5 kg of recycled resin. We considered a yield of 85% between the reception and the pelletising, meaning a need of 15.88 kg of post-consumer EPS waste. To achieve the amount of waste, we needed a total of 11 students, from which 5 were considered to travel by bus and 6 to travel by car. After, for the waste processing, we considered the use of pressurised tap water for the prewashing. A total of 10 gallons per minute is considered here, and 10 minutes per kg of prewashed post-consumer waste. However, a pump was not necessary since the street pressure was enough. For the washing process, we considered a 20 kg washing machine of 700 W electric power. For the drying process, we considered a 20 kg electric drying machine. A total of 0.5 m^3 per kg of washed product was considered here. Additionally, we considered 142 ml of liquid detergent, bleach, and degreaser per kg of washed product, and a total of 57.94 kwh for the processing of the 15.88 kg of waste, with the electricity share of 2019.. Finally, for the waste transformation, we considered that the 15.88 kg of washed and dried post-consumer EPS waste is sent to the grinding, extrusion, and pelletising machine. The only input here was electricity (0.2567 kwh/kg of pelletised product).

Scenario B: considers the case of the same artisanal recycling as in Scenario A, but we shifted the share of renewable energies as set for the year 2027. This is with the objective of finding out the impact of improving the electricity power mix in the industrial processes

Scenario C: For this process, we considered the support of the informal recyclers as established in the 2019 study. We assumed that the informal recyclers will pick the EPS post-consumer waste from the kerbside residues for the collection process. From a previous study, we know that each person produces 2.31 g/day/capita of EPS waste, and there is are an average of 4 people per household and almost 200 households per zone covered by each recycler. A total of 1.848 kg can be expected to be collected daily, and a total of 8 recyclers are needed to achieve 15.88 kg of EPS post-consumer waste daily. After we considered 20 km transport by van to the waste resellers that will do the sorting process, and after we considered 30 km transport by truck to the company. In this scenario we changed the artisanal process and went for a big scale industry production of resin recycled pellets. For the crushing, washing, and drying process, we considered 0.01125 m^3 of tap water per kg of washed product. Additionally, we considered 0.5 ml of liquid detergent, bleach, and degreaser per kg of post-consumer washed waste. Total electricity necessary here was 3.1673 kWh, and we considered the same case of electricity mix as in Scenario A.

3.4 Avoidance of virgin and waste EPS

Considering that the recycling process of EPS post-consumer waste reduces the amount of waste reaching the landfill, while additionally diminishes the same quantity of needed virgin PS resin for the container production process, we considered to compare all three scenarios to the avoided raw material and waste. For the virgin plastic resin production, we considered 13.5 kg of polystyrene expandable granulate. We also considered 89.90 tkm (6,437.376 km x 0.0135 tons) of transport, through transoceanic ship from the American manufacturer to the port of Guayaquil. An additional value of 0.27 tkm (20 km x 0.0135 tons) for transport from port to company was also considered. For the waste disposal, we considered all material to end up in the local landfill.

4. Results and discussion

From the software analysis and calculations according to the scenarios considered, the CF and WF for each scenario is shown in table 1. In addition, the amount apporte for each phase of the process is shown to notice where the major impacts are located.

As the table indicates, the best scenario is C, which considers industrial recycling with the energy mix of 2019. With a total CF of 33.01 kg CO_2eq, most of the impacts are produced during the waste extraction (almost 90%). Scenarios A and B produce more CF than scenario C. It means that artisanal recycling is not the best solution, although it was a first step to demonstrate the possibility of recycling of expanded polystyrene. On the other hand, when comparing scenarios A and B, we can see the benefits that present the increasement in the share of renewable energies, having a high impact on the CF with a diminishment of 22%, but it does not present an impact for the WF, only minimising 0.01 m^3 for sceneario B when compared to scenario A. Logically, the waste processing that consists of prewashing and washing takes almost 100% of the total water depletion for scenarios A, B and C.

Additionally, we can see that scenario C presents better sustainability indicators with values of 33.01 kg CO_2 eq. and 0.03 m^3 eq., representing a minimisation of 33% and more than 92%, respectively. Important to mention, that this comparison is done keeping in mind that the recycling process can help reduce the amount of waste and the necessity of virgin raw material. However, scenario C considers the acquisition of specialised machinery, representing a cost affecting the plastic industry's recycling intentions.

The quantification of CF can be considered an approach to address the potential impact of the production sector on climate change [24]. According to the Centre for International Environmental Law, plastic production reports an emission of 1.89 tonnes of CO2 equivalent per tonne of plastic resin produced [25].

Recycling of food service EPS containers is not widely available due to its economic unfeasibility because of the lack of markets and its contamination with food grease and other substances, which some say can diminish the quality of the recycled foam. However, one study showed that the recycled EPS has a higher tensile strength than raw PS, and the strain at break is very similar, making recycled PS used in the same applications as raw PS [26]. Another research indicated that even plastic wastes originating from mixed municipal solid waste (MSW) could be useful raw materials. The origin and processing method of plastic waste seems not to influence the mechanical quality of the type of plastic [27]. Then it can be concluded that there is a potential to use EPS waste for various applications, reducing the accumulation of solid waste. Furthermore, recycling and reuse of waste EPS can provide a greener and cleaner environment [28].

Enhancing the performance of secondary recycling is required a higher purity and improved sorting. As shown in this study for case scenario C, an optimal environmental recycling performance was obtained where pretreatment (collection and sorting) was adapted with a good recycling technology.

While banning EPS food containers or changing to biopolymers would diminish EPS litter, the truth is that it is possible that it would only change its composition. Littering is a human problem, and the inevitability of littered packaging items will not change based on the product. Additionally, in terms of water footprint, biopolymers, considered widely as very environmentally friendly materials, are a more significant burden to the environment than conventional plastics [29].

Table 1. Sustainability indicators for all case scenarios

Data	Sustainability Indicators					
	CO_2 eq.			m^3 eq.		
	Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C
1. Waste Extraction	13.42	13.42	29.54	0.00	0.00	0.00
2. Waste Processing	55.13	43.13	3.20	2.29	2.28	0.03
3. Waste Transformation	1.62	0.85	0.27	1.26e-04	7.72e-04	2.07e-4
Total	**70.17**	**57.40**	**33.01**	**2.29**	**2.28**	**0.03**

Table 2. Sustainability indicators for the case of raw material extraction and final disposal

Data	Sustainability Indicators	
	CO_2 eq.	m^3 eq.
1. Raw Material	47.89	0.36
2. Final Disposition	1.55	3.31e-05
Total	49.44	0.36

5. Conclusions

The reduction of waste through its transformation into new resources is a priority. Incorporating the processes of reuse, recycling, and recovery is more than necessary since they reduce the consumption of the necessary natural resources and reduce the amount of waste. The great importance of EPS recovery is related to the material's short service life and its high volume.

In this work, a critical analysis has been made on various case scenarios for recovering EPS waste. We use the principles of LCA as the theoretical guiding ideology, and we measure the CO_2 emissions and m^3 of freshwater with the help of SimaPro 9.1 software.

Overall, the total CO_2 emissions for case scenarios A and B are approximately 42% and 16% higher when compared to the values of table 2, but scenario C exhibits a reduction of almost 50%. For the water depletion, scenarios A and B show higher values than those of table 2 with 536% and 534%, respectively. Important to mention that scenario B presents much better values for CF and WF than scenario A, meaning that the increase in the share of electricity production by renewable energies can improve the sustainable production of recycled PS resin.

The determination of carbon and water footprint as indicators of environmental impact may be handy tools for the plastic industry because it enables a more comprehensive analysis of various materials and production processes from a different point of view. Such analysis could be beneficial for engineering processes and materials with the lowest possible impact on the natural environment. It is not enough to have regulations made by the government to control the emissions of these anthropogenic gases. The process agents must understand the impacts of GHG and how these emissions can be reduced. Thus, the accurate determination of CF and WF can be the initial step of a more complex process of managing an organisation's environmental and economic performance.

Future work should try to formalise the informal recycling scheme for the city and an economic feasibility analysis that considers all three presented scenarios.

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