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Implementation of LCA in the Circular Economy context: methodological issues for application in PET packaging

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Abstract

Life Cycle Assessment (LCA) is nowadays one of the most applied methodologies for evaluating the potential environmental impacts of products and systems related to the plastic packaging sector. Nevertheless, the recent increasing interest on Circular Economy principles introduces challenges in its application, addressing towards adjustments to system boundaries and functional units. This research paper underscores the need for LCA models that are both dynamic, adaptable and capable of capturing both (i) the environmental performances of end-of-life processes and (ii) the quality of the materials obtained from them. To this aim, the main literature is taken as reference to compare chemical and mechanical recycling applied to PET. From the outcomes, the need of considering potential quality degradation resulting from increased recycling and reuse operations applied to the input material is well recognized. The study highlights the potential role of LCA to provide comprehensive information, thereby facilitating comparative assertions and offering valuable insights for informed decision-making and the development of sustainable policies within the plastic packaging industry.

Keywords: LCA; Chemical Recycling; Mechanical Recycling; Circular economy; Consequential analysis;

1. Introduction

Life cycle assessment (LCA) is nowadays a recognized methodology for assessing the potential environmental impacts of products and systems, and its application to plastic packaging becomes increasingly relevant in the pursuit of a more sustainable industrial system.

This work aims to present and discuss the existing LCA methodology issues concerning the comparison of two recycling technologies for plastic products .In light of this, the manuscript seeks to propose an innovative methodology which takes into account different aspects regarding the chemical recycling (R-CHEM) and mechanical recycling (R-MEC) processes of polyethylene terephthalate (PET).

The main points selected for a further discussion in this article are:

1. The methodological approach to be applied for a proper comparative analysis (i.e., whether the attributional or the consequential);
2. The choice of the functional unit;
3. In relationship to R-MEC and R-CHEM, the number of process cycles that PET can undergo before reaching an unacceptable quality level for being re-entered into the market;
4. The choice of the more relevant impact categories for the sector.

1.1. Context of the analysis

The analysis is carried out considering Europe (EU) as a geographical area, thus taking into account the European regulations on the Circular Economy (CE) and the data on plastic

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packaging collection and disposal in the continent, provided by Plastics Europe and the EU Parliament.

The EU Directive 2018/852 [1] provides guidelines to (i) prevent the production of packaging waste, and (ii) promote the reuse, recovery and recycling of the packaging waste. Indeed, according to the document, by 31 December 2025, at least 50% by weight of plastic packaging waste must be recycled (the percentege is increased to 55% by the end of 2030). Moreover, concerning the circular economy perspective, the European Commission set an objective to ensure that 10 million tons of recycled PET find their way into new products on the EU market by 2025, with 25% going to bottle application [3, 4].

However, nowadays, the recycling of plastic waste in EU only reaches 32.5% by weight, and one of the main obstacles to achieve the targets set is that half of the plastic collected for recycling is exported to be treated in countries outside Europe [2].

1.2. Background for PET selection

The discovery of plastic materials and their diffusion for the production of everyday single-use objects involved a significant growth of waste due to the disposable nature of plastic and to a weak management system. Due to its relevance on market, PET single-use plastic bottle was chosen as first subject for the REPA (Ecobalances or Resource and Environmental Profile Analysis) study commissioned by The Coca-Cola Company aimed to provide a comparison with glass bottles in regard to their environmental profile among the entire life cycle [5]. PET is also one the major plastic commodities used worldwide [6] and it is considered to be of extreme social utility, being used as a carrier of basic necessities such as water in isolated areas of the planet. Therefore, given its socio-economic relevance, PET has been also selected as a target molecule in our work.

1.3. Mechanical and Chemical recycling of PET

The significant presence of plastics in the supply chain inevitably affects the waste management and the relative environmental impacts. To reduce its environmental footprint and increase the circularity of plastics, one of the best solutions is certainly to extend its life time by improving the recovery and recycling operations.

Currently, the primary process used is the R-MEC one [7, 8], even though new alternatives using thermal, solvolysis, and dissolution technologies are increasing their relevance at the industrial scale (Fig. 1).

Several studies have been published with the aim to better understand the market feasibility, the environmental implications and the potentialities of the currently available recycling methodologies [9, 7, 10, 11]. From there, we can extrapolate that the recycling processes have different environmental footprints and efficiencies, making each method more suitable for specific conditions [12].

According to the international standards regulating LCA [13, 14], there are two different types of recycling processes: the closed-loop, when the material is reintroduced into the same type of process to obtain a similar product, and open-loop, when the material is sent to another process for producing a different product, e.g. fibre [15]. Thus, the closed-loop recycling of bottle-grade PET is usually called bottle-to-bottle (B2B), and the open-loop is called bottle-to-fiber (B2F).

R-MEC consists in: (i) sorting polymer waste streams, (ii) reducing their size and (iii) applying an extrusion process[16]. Mechanically recycled PET (mr-PET) often has to be blended with virgin polymer granulates to meet the desired product specifications due to impurities and quality degradation. Often, some additives are used to accumulate in the recycled resin by limiting its use in the food sector. For this reason, mr-PET is often down-cycled for lower-value applications [17].

On the other hand, R-CHEM is a process applied to transform polymeric waste into materials that can be utilized as secondary raw materials for plastic production by working on its chemical structure. The major technologies for recycling chemicals include pyrolysis, gasification, hydrocracking, and depolymerization. [18]

Conversely to R-MEC, in R-CHEM, there is no loss of material quality due to the shortening of polymer chains since, the polymerization of PET starts with the two monomers as happens in the case of virgin material[18]. Moreover, chemical recycling breaks down polymers into their constituent parts (i.e., monomers), enabling the creation of recycled plastic (recyclate) with virgin plastic grade that can be used in high-quality applications (i.e., food). In general, after the chain breaking occurred the monomers undergo a purification process that allows contaminated or coloured PET to be used as raw materials; this reduces the amount of scraps, increasing the recycling rates and facilitating the sorting operations [17].

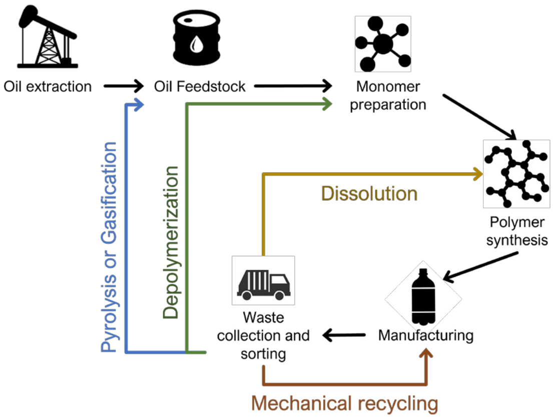

Fig. 1. Chemical and Mechanical recycling scheme, adapted from [18].

Even if the benefits in terms of material saving achievable from the R-CHEM application are noteworthy, the process is not impact free. Alkaline hydrolysis, the reaction mainly used for depolymerization, presents some environmental drawbacks, among which its high energy-intensity, which is translated into an environmental disadvantage if the energy is produced from fossil sources. However, even considering this drawback, R-CHEM still leads to reduce the dependency on virgin PET. In the next paragraph the main aspects that characterize the LCA studies of R-MEC and R-CHEM processes will be critically discussed and counterposed.

2. Materials and methods

2.1. The issue of selection of Declared Unit

Before applying the LCA methodology to plastic recycling processes, there are still some straightforward aspects that should be clarified and harmonized. One of these is the choice of the functional unit, since it may significantly influence and alter final results and comparative trends.

Specifically, the majority of studies primarily focus on the amount of inlet-waste (InW), whether it is normalized to a mass unit [19, 20, 21, 22, 23, 24, 25], to the volume [26, 27], or directly to the quantities generated at regional, national, or even global levels [28, 29, 30]. Some rare cases based on a different approach were also found in literature. One of them is related to the packaging sector and still considers InW as a reference flow, but the focus shifts to the function of the product for which the packaging was produced (i.e., the waste deriving by the amount of packaging produced to pack 1000 L of drinks) [31]. In a second case, related to polyethylene, the functional unit is fixed at 1 kg of product, assuming that the recycled material is qualitatively comparable to the product obtained from virgin resources [32].

The Product Category Rule (PCR) for ”Plastic waste and scrap recovery (recycling) services” [33], which is designed to provide a reference guideline for assessing the environmental performance of plastic waste and its recycling or recovery process, suggests an approach based on InW (so-called declared unit), in line with the common mentioned framework, i.e. 1000 kg of waste plastic. However, it establishes that system expansion (crediting) should be avoided. This statement, together with the recommendation to employ an InW based unit, prevents the comparison of recycled vs virgin PET.

The LCA of virgin PET and other primary plastics should be instead approached by another PCR “Plastics in primary forms” [33], which specifies an output-product based (OuP) functional unit: 1 kg of final product, whether in granules or gel. However, to enable the completion of the inventory, this PCR contemplates the recycling phase, explicitly linking it to the PCR for ”Plastic waste and scrap recovery (recycling) services” [33], only if it is applied to the inlet plastic. Despite the PCR proposes these two different approaches to deal with the cases (i.e., plastic from recycling or plastic from virgin resource), in order to achieve a meaningful impact comparison, the choice of referring to a OuP based functional unit (e.g., 1kg of product) product seems to be the only suitable option to compare recycled PET and virgin PET.

2.2. Life Cycle Assessment approaches for modelling recycling processes

Another aspect which should be carefully addressed is the choice between the two possible approaches for assessing the environmental impact of a product, process or service: the attributional and the consequential [36].

According to the International Reference Life Cycle Data System (ILCD) Handbook [36], attributional modelling is a frame which inventories the inputs and output flows of all processes of a system as they occur. Thus, the attributional method analyses the unit processes involved but does not consider the environmental consequences associated with the market behaviour: it assumes that the chemically recycled PET is directly sent to its consumers instead of existing markets.

The definition of consequential modelling, by ILCD Handbook [36], is: ”Life Cycle Inventory modelling principle that identifies and models all processes in the background system of a system in consequence of decisions made in the foreground system”. The consequential approach, in fact, includes in the evaluation evaluates the market dynamics, by integrating the economic model with the LCA approach and enabling the quantification of the environmental effects caused by including the analyzed process [37].

Table 1 resumes the main advantages and disadvantages of the two Life Cycle Assessment approaches.

Examining a comparison between R-MEC and R-CHEM strategies, in both the cases the InW is assumed to have an impact = 0 (i.e., Cut-off upstream), considering it devoid of economic value. However, the substantial difference lies in the output product. In the case of R-MEC, the output product is, in general, of a lower quality compared to the R-CHEM [24, 38, 11], where it should ideally exhibits the same characteristics and properties of the virgin material [39].

As highlighted in Table 1, achieving a higher-value product provides several advantages, including the complete replacement of virgin material in terms of function with higher avoided environmental burdens. On the other hand, if the intention is to reuse PET for the same purposes for which it was designed, integration with a virgin polyester is necessary to mitigate the loss of quality due to the R-MEC.

In Table 1, both attributional and consequential approaches involve the selection of a functional unit based on the InW, in line with the majority of the mentioned studies in literature.

2.3. Multi-Life Cycle Approach

By following a Multi-Life Cycle approach, the property of a material, in this case PET, to be subjected to a more or less limited number of recycling cycles is included in the evaluation. In this way, a quality reduction of the material, which is proportional to the number of recycling cycles to which PET has been subjected, is assumed. It implies the definition of the number of recycling cycles that a material can undergo before being irreparably damaged or compromised. However, in this approach, the assessment should somehow consider the quality of the OuP, especially when comparing different strategies (e.g., R-MEC and R-CHEM). A lower-quality product can still be classified as an alternative material, with a different function and final usage. Therefore, even though it deviates from the PCR’s recommendation to use an attributional approach, one can consider system expansion by including for R-MEC a

	ATTRIBUTIONAL		CONSEQUENTIAL	
Process	R-MEC	R-CHEM	R-MEC	R-CHEM
System boundaries	Cut-off upstream[a]	Cut-off upstream[a]	Cut-off upstream[a]	Cut-off upstream[a]
Avoided product(s)	PET virgin grade[b]	PET virgin grade[b]	PET low grade[c]	PET virgin grade[b]
Functional unit	Virgin monomer(s) inlet amount[d]	Virgin monomer(s) inlet amount[d]	Inlet waste amount[e]	Inlet waste amount[e]
Integration virgin PET	Higher	Lower	=	=
Impact recycling	Lower	Higher	Lower	Higher
Credit avoided impact	=	=	Lower	Higher

Table 1. Advantages and disadvantages of attributional and consequential approaches.

[a] the inlet waste has an environmental impact equal to 0, as it is assumed to have no economic value

[b] it is assumed to obtain a product with equivalent qualitative properties and functions of virgin PET

[c] it is assumed to obtain a product with lower qualitative properties than virgin PET, therefore the material can be i) mixed with virgin-like PET to be applied for the same function of the original material or ii) be employed for less noble functions

[d] functional unit based on the amount of virgin PET needs to be integrated to allow the final recycling product to have the same qualitative properties of the virgin-like PET, net of the recycling process rate

[e] functional unit based on the inlet waste (independently on the obtained recycling product)

lower-quality (low grade) product compared to virgin-like material as a credit.

In case of R-CHEM, virgin material can be credited since, ideally, the reuse cycles are approximately infinite. However, a percentage loss could occur due to the thermodynamic efficiencies of the system. To our knowledge none standardized data are available on this and, therefore, an estimation can be carried out.

For instance: by considering an efficiency of 90% for the whole recycling process and a consequent loss of the 10% of it as waste, it could be stated that a single monomer can be used for a maximum of ten cycles (after ten cycles, all the original monomer would be replaced by new virgin monomer). The proposed percentages are considered an illustrative example, the real ratio between the recycled monomer and recycled loss should be determined by knowing the efficiency of the process under evaluation, in a site-specific way.

A valid approach is proposed by Gracida-Alvarez and collegues [17]that performed a multicycle analysis with different end-of-life treatment options and recycling technologies, referring to the US context for modelling the disposal scenarios. Five consecutive life cycles are considered with a fraction of virgin, chemically recycled PET and mr-PET for each of them. The comparison between the two recycling strategies (i.e., R-MEC and R-CHEM) can be somewhat contentious. The primary significant aspect is the nature of the two resulting products since, after the recycling process, they have relevant differences in terms of quality, which may affect their employment for identical functions. Assuming the utilization of both products for the same purpose, such as the production of plastic bottles, the quantity of mr-PET within the product is limited to approximately 20% [40], thereby necessitating the introduction of additional virgin PET to compensate the low quality. It means that, per each kilogram of recycled PET introduced in the market, around 4 kilograms of virgin PET must be produced to maintain the same function. Paradoxically, the pursuit of enhancing material circularity through R-MEC, implies an increasing production from virgin sources. However, projections estimates a growth in PET production in the coming years forecasting a 32% increase by 2030 [41]. Consequently, a greater availability of mr-PET would support the predicted production. Projections are attributed to multiple factors, including the alignment with the Sustainable Development Goals (notably, #Clean water and sanitation)[42], the increasing frequency of water scarcity phenomena [43], as well as population growth associated with improved quality of life in certain regions [44]. Another concern related to the mr-PET quality reduction is the limited number of cycles of R-MEC to which PET can be subjected before the polymer chains are irreparably compromised [7, 11]. Such implication result in the need of applying a chemical recycling process or a more traditional waste management (i.e., waste-to-energy or landfilling) to the lower quality PET, reducing the prospects of circularity. In fact, by addressing R-CHEM, since the process allows to obtain a virgin-like characteristics, the amount of introduced virgin PET is only dependent on the recycling rate and not to quality requirements. Unfortunately, the presence of inventories related to the R-CHEM is limited in literature and available databases. For this reason, it is complex to predict both the recycling rate of the process, as well as to estimate the potential environmental impacts. On the contrary, drawing on literature, it is possible to calculate the process yields and environmental impacts of R-MEC, which are anyway considered lower with respect to R-CHEM [45].

2.4. The issue of Impact Categories selection

One of the four fundamental steps of LCA analysis is the impact assessment phase, which includes the choice of method and impact categories for carrying out the assessment. Analysing the articles cited in this paper, it is evident that the most widely used method are the ReCiPe 2016 [34] and the IPCC 2021 [35]. Alternatively, studies are conducted using the Environmental Footprint (EF) method or following the guidelines in the ILCD Handbook [36]. Thus, the impact categories mainly used are Agricultural land occupation, Global Warming, Fossil depletion, Freshwater ecotoxicity, Freshwater eutrophication, Human toxicity, Ionising radiation, Marine ecotoxicity, Metal depletion, Natural land transformation, Ozone depletion, Particulate matter formation, Photochemical oxidant formation, Terrestrial acidification, Terrestrial ecotoxicity and Urban land occupation. Among these categories, however, there are some more relevant ones: Global warming and Fossil resource depletion are central to the major targets on the circular economy of plastic waste, according to Meys et al. [38]. In addition, other categories, such as Terrestrial acidification, Marine eutrophication and Freshwater eutrophication, can also be considered important for PET disposal. In order to assess the renewability of the process, as already done for chemicals [46], cumulative energy demand (CED) can be also included in the analysis. This, as in the case of carbon footprint (IPCC), is a single-issue indicator. In our opinion and according to ISO 14044, multi-impact methods should be always adopted to integrate the environmental profile of the recycling systems under study.

3. Conclusion and future developments

This analysis focused on the recycling of PET, specifically considering R-MEC and R-CHEM approaches. The study investigated the complexities of assessing the environmental impact of these recycling processes, exploring the most critical aspects: the selection of the declared unit, the life cycle assessment approaches for modelling the recycling process, the lack of data, the potential for multiple recycling cycles, and the choice of relevant impact categories. The selection of the declared unit was also discussed, highlighting the need to choose a functional unit based on the output product's quality: this consideration becomes crucial when comparing R-MEC and R-CHEM, given that the first typically results in a lower-quality product, necessitating a higher input of virgin PET to maintain the same function. Moreover, the analysis raised questions about the potential number of recycling cycles a material can undergo before its quality is irreparably compromised.

In conclusion, assessing the environmental impact of PET recycling processes is a complex topic, and various factors need to be considered. These considerations are essential for making informed decisions on how to promote more sustainable plastic recycling practices and achieve circular economy objectives. To address the latter issue a further aspect that can be considered in the future is the the application of the circularity indices according to the ISO 59020 [47], currently under development. They could help to measure the circularity of a product or a system: this could be useful for designing new products, for internal reporting activities, or for setting procurement objectives and, at the company level, they could be used internally for the comparison of different product ranges or for the identification of their progress [48].

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