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CIRCULAR ECONOMY: COMPARATIVE LIFE CYCLE ASSESSMENT OF FOSSIL POLYETHYLENE TEREPHTHALATE (PET) AND ITS RECYCLED AND BIO-BASED COUNTERPARTS

Magdalena Rybaczewska-Błażejowska[1], Angel Mena-Nieto[2]

[1] *Kielce University of Technology, Department of Production Engineering, Poland*
[2] *University of Huelva, School of Engineering, Spain*

Corresponding author:
Angel Mena-Nieto
University of Huelva, School of Engineering
Department of Electrical and Thermal Engineering, Design and Projects
Campus El Carmen, 21007 Huelva, Spain
phone: +34 959217444
e-mail: mena@uhu.es

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Abstract

The transition to circular economy requires diversifying material sources, improving secondary raw materials management, including recycling, and finally finding sustainable alternative materials. Both recycled and bio-based plastics are often regarded as promising alternatives to conventional fossil-based plastics. Their broad application instead of fossil-based plastics is, however, frequently the subject of criticism because of offering limited environmental benefits. The study presents a comparative life cycle assessment (LCA) of fossil-based polyethylene terephthalate (PET) versus its recycled and bio-based counterparts. The system boundary covers the plastics manufacturing and end-of-life plastic management stages (cradle-to-cradle/grave variant). Based on the data and assumptions set out in the research, recycled PET (rPET) demonstrates the best environmental profile out of the evaluated plastics in all impact categories. The study contributes to circular economy in plastics by providing transparent and consistent knowledge on their environmental portfolio.

Keywords

Circular economy, life cycle assessment (LCA), polyethylene terephthalate (PET), polylactic acid (PLA), recycled plastics, sustainable consumption, packaging waste management.

Introduction

Until recently, the majority of economic approaches, followed by the manufacturing industry, have been linear. Raw materials and resources from the natural environment were obtained through mining to manufacture products, and unwanted production by-products and waste materials [1], [2]. Similarly, consumers dispose of the products they use when they have reached the end of their useful life cycles [3–5]. Furthermore, both manufacturing industries and consumers very often dump their wastes into landfills or incineration plants, which leads to negative environmental impacts and a terrific waste of secondary raw materials.

Taking into account, among others, the aforementioned arguments, the concept of a circular economy (CE), as an alternative to the traditional linear model, has attracted increased attention lately. It is characterised, rather than defined, by 3R (reduce, reuse and recycle) to 9R (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover) principles that ought to be applied throughout the whole life cycle of products. The general idea of CE is that economic development requires less resources and energy in production and consumption thanks to using the inner circles [6]. The American Institute of Industrial and Systems Engineers noted that the future economic growth and thus the success of individual production systems will largely depend upon the effectiveness of implementing CE principles and thus reducing the use of natural resources and extracting usable value from existing materials and generated waste [7].

The latest European Union (EU) Commission's plan [8] emphasises that it relies on the stakeholders' active engagement to achieve the European Green Deal [9] to promote the clean production and responsible supply chains through the adoption of closed loop systems. Additionally, the EU has reiterated its commitment to implement the 2030 Agenda for Sustainable Development to protect the natural environment, decrease land degradation and prevent the loss of biodiversity by reducing the reliance on the use of the natural resources [8, 10]. Regarding the sustainability of products, the European Commission promotes, among others, the following actions:

- increasing recycled content in products,
- remanufacturing and high-quality recycling,
- reducing carbon and environmental footprints [8].

Notwithstanding, new technologies and innovative as well as eco-innovative approaches create a great opportunity for the implementation of the EU CE foundations.

One of the greatest concerns of CE is related to plastics. The use of plastics has increased at the rate of 4% a year since 2000 though, despite the fact that it takes more than 400 years to degrade [11]. To date, 79% of plastic waste has been landfilled, 12% has been incinerated and just 9% has been recycled worldwide [12]. Not only do plastics carry a carbon footprint when they are manufactured, but also when they are managed at their end of life, since most plastics still exist in landfills or in our natural environment. Consequently, the European Commission has emphasised that the prevention of plastics and plastic waste should be one of the Commission's first priorities [8]. In this light, many European governments have imposed restrictions on the use of conventional fossil-based plastics, including polyethylene terephthalate (PET).

The environmental concerns regarding plastics and plastic waste make an important contribution to searching for alternatives for fossil-based plastics. Alternatives should be developed and used only if they prove a better environmental profile compared to the conventional fossil-based plastics. Currently, the most often considered ones are recycled and bio-based plastics. The term bio-based plastics implies that the polymer is made from renewable resources or is biodegradable or compostable at the end-of-life [13].

Though environmental profiles of both recycled and bio-based plastics have already been researched, the conducted studies provided very confusing results. They differed, though, in terms of type of plastic being analysed (basically either recycled [14] or bio-based ones [15]), the system boundaries (basically either cradle-to-gate [16] or gate-to-grave [17]) and finally the data set involved. In consequence, it is still impossible to clearly define the environmentally preferable alternative in the European realities.

This research analyses two promising, supposed sustainable alternatives to PET plastics, i.e. 100% recycled PET (rPET) and bio-based plastic, i.e. polylactic acid (PLA), taking into account the EU's propositions about the cleaner production and sustainable behaviours in Europe from the CE perspective. The conventional fossil-based PET is examined as a baseline. The results of the research not only provide a scientific basis for the decision-makers in the EU regarding transformation to CE, but also for the plastics manufacturing industry and the plastic waste managers regarding how to improve their environmental profiles and thus to accomplish strict legal environmental requirements.

Methodology

This research follows the framework of ISO 14040 and ISO 14044 standards regulating the life cycle assessment (LCA). The choice of the methodology was dictated by the comprehensiveness of the LCA technique, which enables accounting and aggregating of environmental aspects and their impacts into one consistent framework, wherever they occur in the life cycle of product [18].

The research is divided into the following stages: goal and scope definition, inventory analysis, life cycle assessment and interpretation [19, 20]. Due to the complexity of the LCA methodology, the research is facilitated with the sophisticated LCA software SimaPro [21, 22].

Goal and scope definition

The goal of the study is to provide as possible consistent and transparent quantitative analysis of the environmental impacts of the conventional fossil-based PET in conjunction with 100% rPET and PLA.

PET is a long-chain polymer from the polyester family [23]. The intermediates of PET are terephthalic acid (TPA) and ethylene glycol (EG), both achieved from oil feedstock [23]. PET is predominantly used for packaging, such as bottles (71%), trays (19%) and flexible packaging (6%) (PET market in Europe, 2020). The popularity of PET as a packaging material stems from its properties, i.e. glass-like transparency and low weight combined with flexibility and mechanical resistance [24].

rPET – post-consumer PET is collected for recycling within its well-established logistic chain in the EU, including collection, mechanical sorting and flake production [25]. Similarly to PET, it is largely used for packaging, specifically bottles as well as trays and sheets [26]. Moreover, the EU introduced requirements for a mandatory minimum content of rPET in beverages bottles placed on the market at the level of 25% starting from 2025 and 30% starting from 2030 [27].

PLA, one of the most frequently used bio-based polymers, is a growing alternative to the conventional fossil-based plastics, including PET. It is made from lactic acid, which is produced through fermentation of renewable agricultural source corn [28]. Subsequently, lactic acid is polymerised to create granulates that are used to make different commercial products, including packaging (nearly 70%) [29]. The commercial application of PLA as a packaging material is not only because of it is made from renewable resources, but largely because of PLA's unique combination of functional properties, including high gloss and clarity as well as very good flavour and aroma barrier characteristics.

The functional unit denoted for this research is 1 metric tonne of plastic. The system boundary covers the plastics manufacturing and end-of-life management stages (cradle-to-cradle/grave variant). Generally, the plastics are made of different raw materials (either petroleum or corn starch) or secondary raw materials (post-consumer PET) at different locations. Transportation was deliberately excluded from the analysis as not to confuse the results. Regarding the end-of-life plastic management, the current EU legislation on packaging and packaging waste requires that a minimum 50% of plastic by weight contained in packaging waste to be recycled in 2025 [30]. It has to be underlined, however, that regarding plastic packaging waste there are already countries in Europe, including the Czech Republic, Spain and the Netherlands, which achieved the aforementioned level of recycling in 2018 [31].

The research follows an attributional approach regarding the manufacturing stage and a consequential approach regarding end-of-life management [32]. The study [33] showed, though, the merits of expanding LCA approaches beyond an attributional approach, in order to present wider systemic effects of change arising from the process being investigated. Indeed, it is a common practice in LCA of end-of-life management that products generated during the adequate waste treatment substitute the corresponding market products, for instance rPET substitutes PET.

Inventory analysis

Data applied in the LCA modeling are retrieved from the existing LCI databases, such as Ecoinvent [34] and Easetech [35]. Consequently, the modelling of the PET manufacturing is based on the average unit process from the eco-profiles of the European plastic industry. The modelling of the rPET manufacturing is based on the PET recycling data for Europe retrieved into the Easetech database from several scientific articles. Finally, the modelling of the PLA manufacturing is based on the data from the world's largest bio-plastics producer, i.e. NatureWorks LLC, located in the USA.

End-of-life management is different regarding PET and rPET, and PLA. As to reflect the market reality as closely as possible, it was assumed that 50% by weight recycling targets of PET and rPET has already been achieved and thus, it is mechanically sorted out and recycled into flakes. PET is, however, the most recycled plastic packaging material in Europe. Regarding PLA, it was assumed that it is a part of commingled waste and is subsequently disposed of in sanitary landfills. PLA derived from packaging, though, is only biodegradable under certain environmental conditions, which can only be achieved at industrial composting facilities. The number of such facilities in Europe is currently very limited. Unfortunately, detailed information on how PLA waste is managed in individual member states of the EU is currently missing [17].

Life cycle impact assessment

The environmental profile of PET, rPET and PLA was calculated with the use of the ReCiPe Midpoint (H)/Europe ReCiPe H/A method [36]. This is, though, a harmonised multi-impact category method at midpoint and endpoint level that allows complex LCIA analyses. The hierarchist (H) perspective was chosen, based on the assumption that the environmental damages are reversible, if proper policy and technological changes are introduced [37].

In view of the above, the inventory data were classified into the following impact categories of possible significant detrimental impact on the environmental: climate change (CC) (kg CO_2 eq), terrestrial acidification (TA) (kg SO_2 eq), freshwater eutrophication (FE) (kg P eq), marine eutrophication (ME) (kg N eq), human toxicity (HT) (kg 1,4-DB eq), particulate matter formation (PMF) (kg PM10 eq), terrestrial ecotoxicity (TET) (kg 1,4-DB eq), freshwater ecotoxicity (FET) (kg 1,4-DB eq), marine ecotoxicity (MET) (kg 1,4-DB eq), natural land transformation – manufacturing stage (NLT) (m^2) and fossil depletion (FD) (kg oil eq).

Results and discussion

Based upon the inventory analysis, environmental profiles of rPET and PLA in comparison to PET were calculated. Transportation was excluded from the research and thus no assumptions regarding transport, including the means of transport and distances, were made.

The research proved that, regarding the manufacturing stage, rPET has the lowest environmental impacts in all categories (Fig. 1). Consequently, the calculated characterization values for rPET in the examined impact categories are as follows: climate change – 284.4 kg CO$_2$ eq, terrestrial acidification – 0.586 kg SO$_2$ eq, freshwater eutrophication – 0.000046 kg P eq, marine eutrophication – 0.0164 kg N eq, human toxicity – 6.26 kg 1,4-DB eq, particulate matter formation – 0.1746 kg PM10 eq, terrestrial ecotoxicity – 0.004958 kg 1,4-DB eq, freshwater ecotoxicity – 0.04913 kg 1,4-DB eq, marine ecotoxicity – 0.03672 kg 1,4-DB eq and fossil depletion – 87.42 kg oil eq (Table 1). Compared to PET, the environmental impacts of rPET are in the range of 0.01–10.16% (Fig. 1). Although there are plenty reasons for such good rPET environmental performance, the predominant one is the cumulative energy demand for recycling, which is far lower than for PET production.

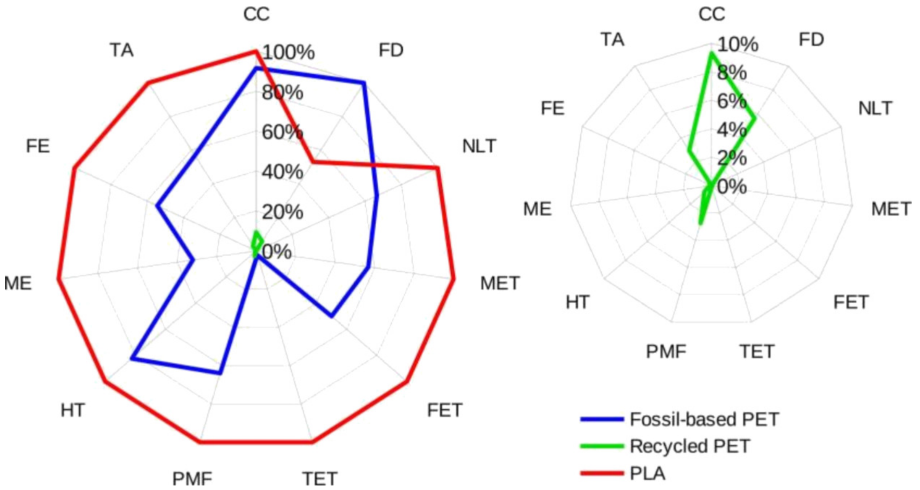

Fig. 1. A comparison of environmental profiles of fossil-based PET versus rPET and PLA – manufacturing stage [in %].

Table 1
Environmental profile of fossil-based PET versus rPET and PLA – manufacturing stage [in units of impact categories].

Impact category	Unit	Fossil-based PET	Recycled PET	PLA
Climate change	kg CO2 eq	2.80E+03	2.84E+02	3.06E+03
Terrestrial acidification	kg SO2 eq	1.14E+01	5.86E-01	2.01E+01
Freshwater eutrophication	kg P eq	6.37E-01	4.60E-05	1.17E+00
Marine eutrophication	kg N eq	3.13E+00	1.64E-02	9.80E+00
Human toxicity	kg 1,4-DB eq	7.67E+02	6.26E+00	9.31E+02
Particulate matter formation	kg PM10 eq	4.06E+00	1.75E-01	6.35E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	1.78E-01	4.96E-03	7.77E+00
Freshwater ecotoxicity	kg 1,4-DB eq	3.32E+01	4.91E-02	6.63E+01
Marine ecotoxicity	kg 1,4-DB eq	3.08E+01	3.67E-02	5.42E+01
Natural land transformation	m2	2.68E-01	NA	4.03E-01
Fossil depletion	kg oil eq	1.56E+03	8.74E+01	8.25E+02

PLA demonstrates the worst environmental performance in nearly all impact categories. The calculated characterization values for PLA in the evaluated impact categories are as follows: terrestrial acidification – 20.1 kg SO_2 eq, freshwater eutrophication – 1.17 kg P eq, marine eutrophication – 9.8 kg N eq, human toxicity – 931 kg 1,4-DB eq, particulate matter formation – 6.35 kg PM10 eq, terrestrial ecotoxicity – 7.77 kg 1,4-DB eq, freshwater ecotoxicity – 66.3 kg 1,4-DB eq, marine ecotoxicity – 54.2 kg 1,4-DB eq and natural land transformation – 0.403 m^2 (Tab. 1). Taking into account biosequestration, the results for climate change are relatively similar – 3060 kg CO_2 eq. Clear environmental advantage occurs only in the field of fossil depletion – 825 kg oil eq, where PLA has 47.12% lower environmental impacts compared to PET (Fig. 1). The negative environmental profile of PLA is basically due to the agricultural processes involved in corn production and related to it – the consumption of energy, the use of fertilizes and pesticides, and finally the overall emissions to air. Thus ecotoxicity (terrestrial, freshwater and marine), natural land transformation and eutrophication (freshwater and marine) are the focal concerns of PLA manufacturing. In the future, digital and precision farming might slightly reduce these impacts on the environment. The evaluation of any prospective scenarios in this regard is, however, beyond the scope of this research.

The LCA results showed that regarding the manufacturing and end-of-life management stages again rPET has the best environmental performance (Fig. 2). Consequently, the calculated characterization values for rPET in the examined impact categories are as follows: climate change – −721 kg CO_2 eq, terrestrial acidification – −4.47 kg SO_2 eq, freshwater eutrophication – 0.0732 kg P eq, marine eutrophication – −0.0827 kg N eq, human toxicity – 5.70 kg 1,4-DB eq, particulate matter formation – −1.68 kg PM10 eq, terrestrial ecotoxicity – 7.81 kg 1,4-DB eq, freshwater ecotoxicity – 0.295 kg 1,4-DB eq, marine ecotoxicity – 0.219 kg 1,4-DB eq and fossil depletion – −479 kg oil eq (Table 2). In view of the above, comparable results are only in the category of terrestrial ecotoxicity, where rPET offers 2% savings (Fig. 2).

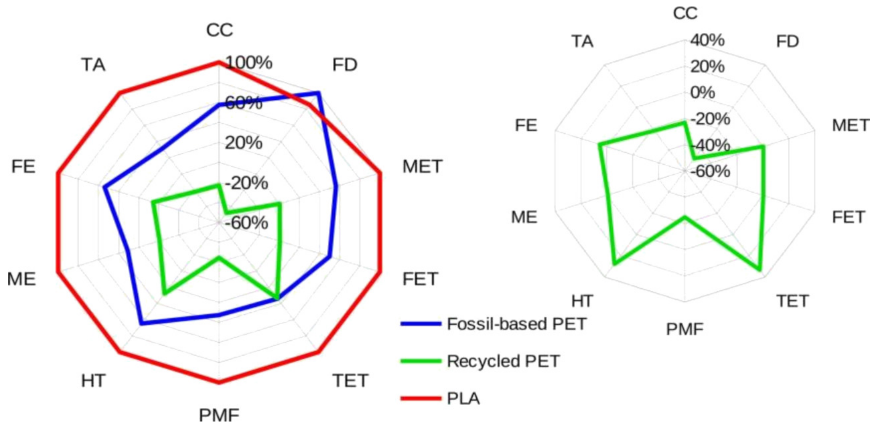

Fig. 2. A comparison of environmental profiles of fossil-based PET versus rPET and PLA – manufacturing and end-of-life management stages [in %].

Table 2
Environmental profile of fossil-based PET versus rPET and PLA – manufacturing and end-of-life management stages [in units of impact categories].

Impact category	Unit	Fossil-based PET	Recycled PET	PLA
Climate change	kg CO2 eq	1.80E+03	−7.21E+02	3.13E+03
Terrestrial acidification	kg SO2 eq	6.35E+00	−4.47E+00	2.03E+01
Freshwater eutrophication	kg P eq	7.10E-01	7.32E-02	1.32E+00
Marine eutrophication	kg N eq	3.03E+00	−8.27E-02	9.81E+00
Human toxicity	kg 1,4-DB eq	1.33E+03	5.70E+02	2.05E+03
Particulate matter formation	kg PM10 eq	2.21E+00	−1.68E+00	6.78E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	7.98E+00	7.81E+00	2.34E+01
Freshwater ecotoxicity	kg 1,4-DB eq	3.34E+01	2.95E-01	6.67E+01
Marine ecotoxicity	kg 1,4-DB eq	3.10E+01	2.19E-01	5.50E+01
Fossil depletion	kg oil eq	9.94E+02	−4.79E+02	8.48E+02

The predominant reason for the good environmental profile of rPET is the substitution of PET and thus the avoidance of linked environmental impacts.

As for the manufacturing stage, PLA has the worst environmental performance during the manufacturing and end-of-life management stages. In view of the above, PLA generates the following environmental problems: climate change – 3130 kg CO_2 eq, terrestrial acidification – 20.3 kg SO_2 eq, freshwater eutrophication – 1.32 kg P eq, marine eutrophication – 9.81 kg N eq, human toxicity – 2050 kg 1,4-DB eq, particulate matter formation – 6.78 kg PM10 eq, terrestrial ecotoxicity – 23.4 kg 1,4-DB eq, freshwater ecotoxicity – 66.7 kg 1,4-DB eq, marine ecotoxicity – 55.0 kg 1,4-DB eq) and fossil depletion – 848 kg oil eq (Table 2). Only in the case of the latter, PLA offers 15% environmental benefits compared to PET (Fig. 2). It has to be stressed, however, that the former LCA studies on end-of-life management of PLA have already proved that all other waste management options, namely recycling (material and organic) or thermal treatment, perform better from an environmental perspective than landfilling [38]. Nevertheless, in order to realise the recycling, for instance, first, the share of PLA waste needs to increase considerably and, second, an adequate infrastructure must be established.

Owing to the fact that CE is a relatively new concept and the comparative LCAs of alternatives to conventional fossil-based plastics are still in its infancy, the current research is not free of limitations. Lack of high quality foreground data on plastics production, representing the same time-related, geographical and technological coverage is a predominant source of limitations for the achieved results. As opposed to the fossil-based and recycled plastics, the bio-based plastics are relatively immature packaging materials (10–20 years on the market), manufactured outside Europe in a limited number of facilities, relying on emerging technologies [39].

Conclusions

Circular economy is, in general, an interesting contribution to sustainable development; however, there are still several trends that need further in-depth studies. This is exactly the case when it comes to substituting conventional fossil-based plastics, including PET, with alternative recycled and bio-based plastics. Thus, the presented research constitutes another voice in the discussion on this thought-provoking issue.

It can be concluded that in the current European realities, rPET offers important environmental benefits compared to conventional fossil-based PET during the manufacturing and end-of-life management stages. And conversely, PLA does not show clear environmental advantages over PET neither at the manufacturing stage nor at the end-of-life management stage. Furthermore, the current waste management practices strongly question the sustainability of PLA. Consequently, only when PLA is fully derived from landfills and is destined to material recycling or composting, it can be perceived as an alternative to PET. It still poses a moral question – whether increasing bio-based plastics production is a good idea when an increasing number of people worldwide suffer from hunger and malnutrition.

The results of the research correlates with the long-term ambition of the EU-28 that the PET market will move towards being 100% recyclable, with 100% recycled content (PET market in Europe, 2020). This requires, however, improvements in both the quantity and quality of PET collection, sorting and reprocessing.

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