REVIEWED ARTICLE

DOI: 10.15199/42.2023.1.2

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LIFE CYCLE ASSESSMENT OF (BIO)DEGRADABLE POLYMERS AS A TOOL TO ACHIEVE THE GOALS OF THE CIRCULAR ECONOMY

ABSTRACT: Closed-loop economy initiatives in Europe are still at an early stage. Progress in its implementation in industrial sectors, however, requires clarifying the concept from the perspective of balancing aspects covering environmental, economic and social issues, which may support the transformation process. Green polymer materials made from (bio)degradable, renewable, or recycled raw materials can help prevent and partially reduce waste and contribute to more sustainable life cycles. Furthermore, such materials could have a lower carbon footprint and, in some cases, may exhibit more favourable material properties in many applications. The article is an attempt to show that a systematic, standardised approach to quantifying the potential impacts of a product or process that takes from resource extraction to the end of a product life, such as life cycle assessment, can be an effective methodology for implementing sustainability in the circular economy.

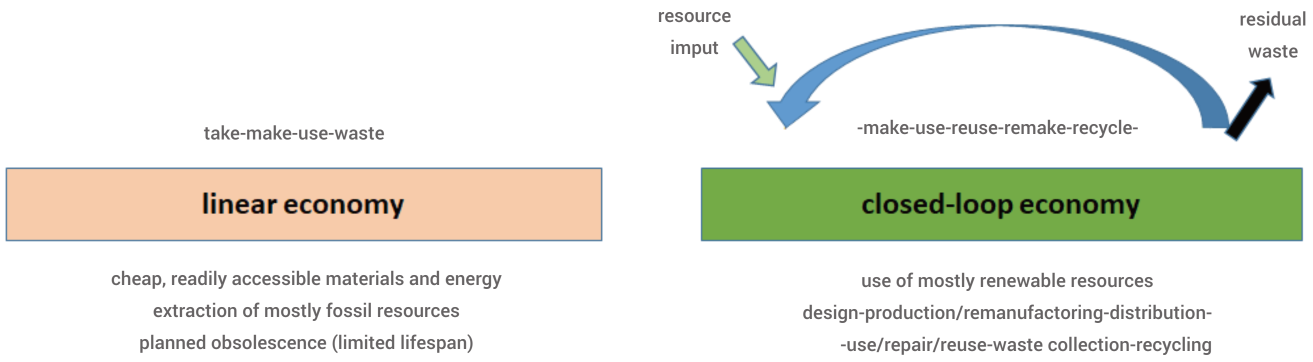
Key words: green polymer, (bio)daegradable polymer, life cycle assessment, circular economy

STRESZCZENIE: Inicjatywy dotyczące gospodarki o obiegu zamkniętym w Europie są wciąż na wczesnym etapie. Postęp w jej wdrażaniu w sektorach przemysłowych wymaga jednak wyjaśnienia tej koncepcji z perspektywy równoważenia aspektów obejmujących kwestie środowiskowe, ekonomiczne i społeczne, co może wspomóc proces transformacji. „Zielone" materiały polimerowe pochodzące z surowców (bio)degradowalnych, odnawialnych lub pochodzących z recyklingu mogą pomóc w zapobieganiu powstawania odpadów i częściowemu ich ograniczeniu oraz przyczynić się do bardziej zrównoważonych cykli życia. Ponadto takie materiały mogą mieć mniejszy ślad węglowy i w niektórych przypadkach mogą wykazywać korzystniejsze właściwości w wielu zastosowaniach. Celem artykuł jest wykazanie, że systematyczne, ustandaryzowane podejście do kwantyfikacji potencjalnych wpływów tych procesów począwszy od pozyskania surowców do utylizacji produktu, takie jak ocena cyklu życia, może być skuteczną metodologią wdrażania zrównoważonego rozwoju w gospodarce o obiegu zamkniętym.

Słowa kluczowe: zielony polimer, polimer (bio)daegradowalny, ocena cyklu życia, gospodarka o obiegu zamkniętym

INTRODUCTION

The European Union (EU), producing more than 2.5 billion tonnes of waste a year, has forced the European Parliament to take appropriate legal action and update waste management regulations as well as promote the transition to a more sustainable model known as the circular economy [1]. Circular economy "is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible" [2]. This means use of raw materials more efficiently, reducing



PIC. 1. LINEAR ECONOMY VS CIRCULAR ECONOMY MODEL

waste to a minimum, and extending the life cycle of products through repeated use (repair, reuse, recycling) (see Pic. 1).

The principles of the circular economy are based on minimising waste and pollution, streamlining the circulation of products and materials in effect resource efficiency (countries depend on raw materials, the world's population is growing, and the supply of key raw materials is limited), and regeneration of nature, including primarily reducing emissions of greenhouse gases, and contributing to the preservation of biodiversity (extracting and use of raw materials destroys environment and increases energy consumption and carbon dioxide (CO_2) emissions). In the long run, waste prevention, eco-design and reuse can save businesses and consumers money. Environmental pressures will be reduced, security of supply of raw materials will increase, and competitiveness and innovation of companies and products will rise, resulting in economic growth. Thus, a circular economy can support the goals of reducing overconsumption of natural resources while providing economic benefits [2,3].

However, circular economy concept applied to real business cases it is still at an initial stage. Closed-loop business models require industrial implementation that faces more barriers than enablers. Circular economy is a management model and a systemic way of thinking. It is a more complex issue, supporting systems thinking as an integral part of the circular economy concept [4,5]. Despite various policy instruments to accelerate the transition from a linear to a circular economy, there are gaps in supply chains transparency, weak enforcement of EU waste legislation, limited use of closed-loop criteria in public tenders, and lack of standards and inconsistency in requirements across policy areas. There is also a lack of label of closed-loop products, knowledge-sharing platforms, business partnerships, financial incentives, awareness-raising campaigns and, above all, monitoring of progress towards circularity and investment in upscaling promising innovations [6,7].

It is optimistic that European companies are increasingly adopting closed-loop business models, however, focused mainly on operational efficiency and waste reduction (recycling, energy recovery and waste management), and there is a shift from product-based to service-based business models, but corporate culture, market factors and system complexity seem to be obstacles to this. Nevertheless, co-design, production, consumption, and reuse as part of the product life cycle are still poorly implemented [7].

Clarifying the concept of the circular economy from the perspective of balancing environmental, economic and social aspects and highlighting the knowledge gaps and aspects of the framing, implementation and evaluation of circular economy policies, as well as the importance of product-related aspects such as eco-design, incentives for innovation, business models, production and consumption trends are key to the success of the transition, and economic, technical, quality, sustainable and management tools should support the transformation process [8,9].

PLACE OF (BIO)DEGRADABLE POLYMERS IN THE CIRCULAR ECONOMY

Green polymers, i.e. polymers in line with the concept of sustainable chemistry, fit perfectly into a closed-loop economy. Products and processes that reduce or eliminate the use or production of substances that are hazardous to humans, animals, plants, and the environment are in line with the concepts of pollution prevention and zero waste on both laboratory and industrial scales. Green chemistry encourages the use of economical and environmentally friendly techniques that not only improve efficiency, but also reduce waste disposal costs at the end of a chemical process. However, green polymers do not necessarily mean environmentally friendly or bio-based polymers [10]. Environmentally friendly, degradable, or biodegradable polymers are aimed at providing materials with specific, time-limited applications in various sectors, especially in packaging and medical. However, more and more research is being done on long-term applications such as cosmetics packaging [11,12]. Differences in the terminology of environmentally friendly polymers are sometimes minor, but important as they indicate their properties and define their suitability and applications. According to the International Union of Pure and Applied Chemistry (IUPAC) terminology [10], degradable polymers are defined as “polymers in which macromolecules are able to undergo chain scissions, resulting in a decrease of molar mass.” Biodegradation is “caused by enzymatic process resulting from the action of cells”, but in vivo degradation resulting “only from hydrolysis by the water present in tissues and organs” must be referred to as hydrolytic degradation, while degradation taking place by isolated enzymes, an in vitro abiotic process, is “degradation caused by the catalytic action of enzymes” and is not considered biodegradation. The prefix “bio” gives words a strictly defined meaning (biomaterials, biopolymers, bioplastics, bio-based polymers, biodegradation). Biomaterials are “materials exploited in contact with living tissues, organisms, or microorganisms”; such as bio-based materials “composed or derived in whole or in part of biological products issued from the biomass” (plants) does not mean biodegradable materials, although they may be. Bio-based polymers have the same characteristics as regular polymers and may have the extra benefit of having a lower carbon imprint on the environment. What is bio-based is not necessarily biodegradable, and conversely not all biodegradable polymers are bio-based.

Biopolymers and bioplastics also differ significantly. Biopolymers are macromolecules formed by living organisms (including proteins, nucleic acids, and polysaccharides). They always undergo microbial degradation as they are created by nature, although they are not necessarily compostable. Talking about biopolymers, we limit ourselves only to natural polymers [13]. According to European Bioplastics, a plastic material is defined as a bioplastic if it is either bio-based, biodegradable, or features both properties [14]. According to the American Society for Testing and Measurement (ASTM) compostable plastics are defines as “capable of undergoing biological decomposition in a compost site as part of an available program, such that the plastic is not visually distinguishable and breaks down to CO_2, water, inorganic compounds, and biomass, at a rate consistent with known compostable materials (e.g. cellulose), and leaves no toxic residue” [15]. In individual countries, the conditions for both composting and biodegradation are covered by specific regulations (defining technological conditions in the form of technical standards) [16].

(Bio)degradable polymers made from renewable or recycled raw materials can help prevent and partially reduce waste and contribute to more sustainable life cycles. To produce such polymers materials with lower carbon imprint is used, and the end product can be reused (to a lesser extent, e.g. (bio)degradable polymer technological waste can be reused as an additive to make a new product) or recycled mainly organically (turned into compost or biogas). (Bio)degradable plastics could be a viable solution to decrease the impact on climate change and may, in some cases, exhibit favourable materials properties especially in medical applications. The use of (bio)degradable polymers also has some drawbacks, such as negative effects on agriculture – competition with food production, higher costs, and still unclear regulation for the end-of-life management of such polymers. There is also a lack of financial incentives and efforts to move from niche polymers (current production does not exceed 0.5% of the total plastics production) to larger-scale market applications, which would lead to a real sustainable impact [17,18].

Not all conventional polymers should be replaced by (bio)degradable polymers, but there are several key products and applications that can enhance the benefits and contribution of (bio)degradable plastics to the closed-loop economy such as compostable plastic bags for bio-waste, fruit and vegetable, lightweight shopping bags, coffee capsules and tea bags, cosmetic packaging, compostable fruit labels, thin film applications for fruits and vegetables packaging, dog poop bags, or agricultural mulch films. Compostable bio-waste bags for the selective collection of organic waste (other compostable bags can also be used for this purpose) reduce the rate of misthrow of conventional plastics in the organic waste stream. Organic contents (coffee or tea, cosmetics or oils leftovers, and poop) or fruits and vegetables, and their packaging (capsules, bags, bottles or jars, and thin films) or labels made of fully compostable plastics are not an obstacle to composting together [19]. Therefore, biodegradable polymers should be used mainly in agriculture, medicine, pharmaceutical sciences, and packaging [11,12,20].

Bio-based and (bio)degradable polymers are erroneously confused with each other as eco-friendly materials, while the concept of their use differs significantly. (Bio)degradable polymers have been developed from the viewpoint of biodegradability in order to reduce plastics wastes, whereas, for bio-based polymers, biomass is used just as the raw material for production. Nowadays, polymers are usually classified into four main groups given their biodegradability and raw materials origin [21,22]:

- non-biodegradable fossil-based polymers, e.g., polyethylene (PE), polypropylene (PP), polystyrene (PS), poly(ethylene terephthalate) (PET), or poly(vinyl chloride) (PVC);
- bio-based or partially bio-based non-biodegradable polymers, e.g., bio-based PE (bio-PE), PP (bio-PP), or PET (bio-PET);
- polymers that are both (bio)degradable and bio-based, e.g., poly(lactic acid) (PLA), polyhydroxyalkanoates (PHA) such as polyhydroxybutyrate (PHB) and poly(hydroxybutyrate-*co*-hydroxyvalerate (PHBV);
- polymers that are based on fossil resources and are (bio)degradable, e.g., polycaprolactones (PCL), poly(butylene succinate) (PBS), poly(butylene adipate-*co*-terephthalate) (PBAT), or poly(vinyl alcohol) (PVA).

The most common fossil-based polymers i.e., polyolefins (PE, PP, etc.), PET, polyamides (PA6, PA66 etc.), have undoubtedly contributed to the development of human society. However, due to their non-biodegradability all fossil-based polymers are usually considered non-biodegradable. Whereas a lot of oil-based polymers are confused as non-biodegradable i.e., PCL, PBS, PBAT etc. are in fact biodegradable. It is because these polymers possess ester bonds in chemical structure, which are easily degraded in the appropriate environment or by some enzymes secreted by microorganisms. On the other hand, bio-based polymers are usually thought to be biodegradable. However, 100% bio-PE is not biodegradable, although is synthesised from bioethanol, which is produced as a fermentation of glucose process. As well as, non-biodegradable bio-PET is produced from biomass with the use of bio-based ethylene glycol (biomass content in bio-PET is approx. 30%) [23]. Therefore, polymers do not have to be necessarily also (bio)degradable, since the (bio)degradability feature of polymers depends on their chemical structure, not the carbon source.

LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is a systematic, standardised approach to quantifying the potential environmental impacts of a product or process (ecosystems, human health and resources used) that occur from resource extraction to end of life (cradle-to-grave) and can be an effective methodology for implementing sustainability in the circular economy (cradle-to-cradle).

Due to its quantitative approach, LCA accounts for all the material, energy, emissions, and waste flows characterising the system under investigation. It calculates the potential environmental impacts associated with all the life cycle phases.

The methodology is defined and regulated by the ISO 14040 and 14044 standards [24,25]. The analysis shall be performed following the principles of the four main steps:

1. Goal and scope definition;
2. Life cycle inventory (LCI);
3. Life cycle impact assessment (LCIA);
4. Interpretation of results and improvement of the analysis.

In the first phase, the study goal and objective are defined, specifying the methodological framework and the primary approach of the study, defining several key aspects, such as the system boundaries and the reference unit. The LCI step lists and quantifies all the inputs and outputs flow, gathering process data and information of all the considered life cycle phases. The LCIA step quantifies and accounts for the environmental impact generated by all the life cycle phases, starting from the process data gathered in the LCI step and applying several impact assessment models to calculate the potential burdens of the system on different environmental categories and indicators. Finally, in the interpretation and improvement step, recommendations and conclusion are outlined, the main critical points (i.e., environmental hotspot) are identified, and suggestions on how to improve the LCA analysis and, at the very end, the environmental impact of the whole system are provided.

MEASURING CIRCULARITY WITH LCA

There are many different methodologies and metrics that can be employed to measure circularity [26]. The recent ISO Technical Committee (TC232) has been established with the intent to propose a common strategy for measuring circularity. The aim of the technical committee is to develop new guidelines to implement and assess circular economy strategies [27]. Although it is not yet clear how LCA-based methodologies can be a consistent support for evaluating sustainability in the context of circular economy, LCA has already been revealed as a powerful tool to assess the environmental performance of a system from a holistic point of view, with an eco-design perspective. This means that LCA can be applied to evaluate the potential future environmental impact of a system at an early-stage technological development, supporting future decisions and development strategies. This feature of the LCA methodology is crucial for evaluating sustainable circular economies because it enables the assessment of environmental performances and circularity of a system and the comparison of different circular economy strategies. The ability of LCA and LCA-based methodologies to bring a holistic perspective and an environmental, social, and economic evaluation into decision-making, put such methodologies in a pivotal role when providing robust technical support in terms of finding the trade-offs between a large set of impact indicators, assessing the overall sustainability of circular economy systems [28]. For instance, developing and implementing a circular economy project that aims to replace single-use plastics in the EU should be supported by various technical information and findings considering all environmental, social, and economic consequences of setting up such a flagship circular economy strategy [24]. However, it should be noted that several challenges need to be faced and overcome for a robust application of LCA and LCA-based methodologies to support the decision-making in the context of circular economy strategies [25].

LCA OF (BIO)DEGRADABLE POLYMERS

In recent years, the interest of the scientific community regarding the application of LCA and LCA-based methodologies to bio-based and (bio)degradable polymers raised massively. Performing an analysis of the life cycle sustainability of these innovative products is pivotal for an auspicial decrease in the future environmental impact of the polymer production sector, ensuring a practical application of circular economy strategies. Several scientific papers, technical reports, and position papers have been published in a very short time, and many essential outcomes and evidence have been revealed [29-32].

One of the most important outcomes is provided by some review papers on applying LCA to compare the environmental impact of conventional fossil-based vs (bio)degradable polymers. When considering the large amount of environmental impact results and findings, it is broadly accepted that one of the most specific outcomes is that there is a lack of agreement on the real best-performing polymers, whether suggesting that fossil-based is always worse than (bio)degradable in any impact category [33,34]. This is mainly due to the different choices made in the modelling set-up, particularly LCA assumptions, the allocation method employed, and the definition of system boundaries. The latter seems to be one of the key issues to be addressed in order to properly assess the environmental impact of (bio)degradable polymers. The importance of including the end-of-life (EoL) phase in the LCA has been highlighted as fundamental to having a complete carbon biogenic account. In fact only the inclusion of EoL stage can assure a balance between the carbon uptake taking place during the feedstock cultivation phases and the carbon emissions during the EoL. To avoid the dealignment among different LCA approaches, which could lead to a misinterpretation of the real sustainability of bio-based and (bio)degradable polymers, the European Commission (EC) and the Joint Research Centre (JRC) in particularly put much effort into investigating and developing a sustainable alternative to conventional fossil-based polymer production [35]. This effort resulted in the publication of a report which addressed all the methodological issues of applying LCA for the evaluation of the environmental impact of bio-based and (bio)degradable polymers. The mentioned report suggests a detailed standardised approach based on the product environmental footprint (PEF) methodology [36,37]. The main objective of PEF is to establish a standardised methodology for measuring and communicating the life cycle environmental performance of a system. It aims to spread a systematic approach to assessing the life cycle environmental footprint of products and organisations, supporting European policies and policymakers. The standardised approaches, principles, and guidelines described in the report have been defined through a review of several studies that applied the LCA to bio-based and (bio)degradable polymers. This report allows for considering all the reasonable methodological steps and parameters to be addressed in setting up a cradle-to-grave LCA of bio-based and (bio)degradable polymers and the comparison with fossil-based ones. One of the most relevant steps is the accounting of biogenic carbon emissions and removals throughout the whole life cycle, starting from the raw material acquisition (i.e., cultivation of feedstock) to the EoL management.

The proper assessment of the raw material acquisition and pre-processing goes through the analysis of the primary biomass sources supply chain, including all the agricultural production processes needed to (i) prepare the land, (ii) biomass cultivation and the use of fertilizers and pesticides (if any), (iii) convert the biomass into the intermediate chemical compound, and (iv) the final polymerisation to obtain the rough (bio)degradable polymer. During the raw material acquisition and pre-processing phase, one of the most significant impacts that need to be adequately addressed is the greenhouse gas (GHG) emissions occurring as an effect of land use change (LUC). This impact could be direct (dLUC) or indirect (iLUC), and they should be accounted for and described among the LCA results. This is commonly done when there is the need to assess in the LCA all the anthropogenic procedures which require the exploitation of a large area of land, such as feedstock cultivation. dLUC occurs when there is a transformation of one land use type to another, resulting in a remarkable change of the properties of the land, without influencing neighbouring systems (i.e., the conversion from forestland to cropland), while iLUC occurs when a transformation of a land use type also affected other land types outside of the investigated land boundaries [31]. Considering these impacts and establishing an approach to account for them (especially iLUC might be very challenging to assess) is essential to avoid an underestimation of the environmental sustainability of (bio)degradable polymers [31]. Another issue highlighted as critical by many studies in evaluating the environmental impact of (bio)degradable polymers is the modelling of EoL, which is strictly linked with the balance of biogenic carbon accounted for in the raw material acquisition phase. In fact, the quantification of the carbon uptake during biomass cultivation should always be balanced with the carbon emissions at the EoL, which makes modelling EoL processes essential for a reliable environmental assessment. Thus, applying a standardised approach to model the different processes occurring at the EoL of (bio)degradable polymer is essential. The JRC report provides technical solutions starting from applying the circular footprint formula (CFF) [31].

The CFF is a mathematical formula that aims to balance the environmental burdens and benefits of different EoL options in terms of recycling, energy recovery, and landfill. The final environmental impact calculation is performed through several parameters, which are defined based on many technical aspects related to the defined system boundaries, the quality of materials used in the life cycle, the technologies employed, the market sector of the products, etc.

Dealing with modelling EoL treatment of (bio)degradable polymers means that many peculiar aspects should be addressed appropriately. The main one is the polymers' biodegradability (or biodegradation rate), which should be product-specific information due to the high range of variation among different types of (bio)degradable polymers. However, the JRC report provides a detailed description of how to deal with the lack of information on biodegradability, reporting several alternatives based on different characteristics of the (bio)degradable polymers and EoL treatment conditions [31]. All the EoL options should be evaluated through scenario modelling. The specific ones related to the (bio)degradable polymers not used in the agri-food market sector are industrial composting through aerobic or anaerobic digestion (with the on-land application of resulting organic residues), mechanical recycling, incineration, and landfilling.

Industrial composting

Composting is a biological process that converts biodegradable waste into several products due to the action of enzymes. Under aerobic conditions, the waste is converted into inorganic chemical compounds (i.e., CO_2, water, methane, non-methane volatile organic compounds, and other minor elements) and a residual solid fraction, the compost. The latter can be used as a soil amendment, and it might be a possible replacement for mineral fertilizer. From an LCA point of view, this means that a potential environmental credit evaluation could be addressed for this product, but only if the same approach has been followed to model appropriately the above-mentioned agricultural cultivation procedures to guarantee the right balance between environmental burdens and credits.

The anaerobic digestion process is like the aerobic one. The difference is that the biodegradation occurs under anaerobic conditions, enabling the production of biogas (i.e., a mixture of a few gases that depends on the composition of the (bio)degradable waste in input) and the possible following upgrading to bio-methane. Both biogas and bio-methane can be used as fuel to produce energy or used in vehicles. Anaerobic digestion also produces a residual solid fraction that could undergo aerobic digestion to produce a more stable soil amendment. From an LCA point of view, fuel production can play a crucial role in accounting for potential environmental credits on the overall assessment of the (bio)degradable polymers' life cycle.

Mechanical recycling

In conventional mechanical recycling, the polymer wastes are sorted and shredded to be used as secondary raw material to produce new polymer-based products. This process can also be applied to (bio)degradable waste to produce secondary (bio)degradable polymers used to make new products via the “drop-in” process. However, because of physic-chemical characteristics, this process can’t be applied to all the (bio)degradable polymers. In terms of LCA analysis, under certain conditions and through the evaluation by applying the CFF, the recovery of (bio)degradable polymers could avoid the production of the primary one, leading to a potential environmental credit.

Incineration and landfill

Incineration and landfill processes should be used to model the share of (bio)degradable waste which cannot undergo the composting and recycling processes. Ideally, a poor amount of waste should be treated via incineration or landfill because the (bio)degradable polymers should be appropriately collected and sorted to be recycled via industrial composting processes to have a closed loop life cycle, enabling the circularity of the (bio)degradable polymers products.

CONCLUSIONS

The article presents ways of valuation of the environmental impacts of (bio)degradable polymers, which is necessary due to their growing importance in the circular economy. A closed-loop economy is a concept aimed at rational use of resources and reducing the negative environmental impact of manufactured products, which should remain on the market as long as possible, and waste generation should be minimised as much as possible. The (bio)degradable polymers such as PLA, PHA, and aliphatic-aromatic polyesters, fit well into the concept of the circular economy and appear to be a good alternative to conventional plastics. LCA is a tool supporting the achievement of circular economy goals, whether it concerns green polymers, including (bio)degradable polymers, or other existing environmentally friendly products or services.

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ACKNOWLEDGEMENTS: This work was supported by the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 872152, project GREEN-MAP and an international project co-financed by the program of the Minister of Science and Higher Education entitled “PMW” in the years 2020-2023; contract No. 5092/H2020/2020/2.