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APPLICATION OF LIFE CYCLE ASSESSMENT IN THE PACKAGING SECTOR FOR THE ENVIRONMENTAL ASSESSMENT OF POLYMER AND BIOPOLYMER BASED MATERIALS – A REVIEW

PRIMENA PROCENE ŽIVOTNOG CIKLUSA U SEKTORU AMBALAŽE ZA POLIMERNE I BIOPOLIMERNE MATERIJALE – PREGLED

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ABSTRACT

Among many important requirements for packaging materials, environmental friendliness is a property that has become necessary for any material that needs to be competitive in the market. Life Cycle Analysis (LCA) is an analytical instrument that provides a framework for analyzing the impact of products and services on the environment, i.e. provides an understanding and the possibility of comparing different products. LCA studies the use of resources and the consequent emissions of pollutants on the environment during the entire life of a product from raw materials exploitation, through production, use and treatment at the end of the life cycle - recycling and final disposal. This paper will provide an overview of the LCA results of various commercial polymer packaging materials, as well as the results of LCAs of biopolymer materials. Although LCA faces the problem of data heterogeneity, since some studies focused on individual segments of the analysis, while some related to all aspects of the process, as well with the problem of interpreting heterogeneous results, because the output parameters were arbitrarily selected by the researcher, still it could be concluded that the available LCA studies and environmental assessments support further development of biobased polymers. When comparing biopolymer materials with commercial synthetic polymers, they have advantages - lower consumption of fossil fuels and lower emission rate of greenhouse gases from the whole life cycle.

***Key words**: life cycle, packaging, polymers, biopolymers.*

REZIME

Među mnogim važnim zahtevima koje moraju ispunjavati ambalažni materijali, ekološka prihvatljivost je svojstvo koje je postalo neophodno za svaki materijal koji treba da bude konkurentan na tržištu. Analiza životnog ciklusa (LCA) je analitički instrument koji obezbeđuje okvir za analizu uticaja proizvoda i usluga na životnu sredinu, odnosno pruža razumevanje i mogućnost poređenja različitih proizvoda. LCA proučava korišćenje resursa i posledice emisija zagađujućih materija po životnu sredinu tokom celokupnog životnog veka proizvoda od eksploatacije sirovina, preko proizvodnje, upotrebe i postupanja na kraju životnog ciklusa, odnosno recikliranja i konačnog odlaganja. Ovaj rad se bavi prikazom rezultata LCA analiza različitih komercijalnih polimernih ambalažnih materijala, kao i rezultata LCA analiza biopolimernih materijala. Iako se LCA suočava sa problemom heterogenosti podataka, jer se neke studije fokusiraju na pojedinačne segmente, a neke se odnose na sve aspekte procesa, kao i sa problemom interpretacije heterogenih rezultata, jer izlazne parametre proizvoljno bira istraživač, ipak se može zaključiti da dostupne LCA studije i ekološke procene podržavaju dalji razvoj biopolimernih polimera. Kada se uporede biopolimerni materijali sa komercijalnim sintetičkim polimerima, oni imaju prednosti – manju potrošnju fosilnih goriva i nižu stopu emisije gasova staklene bašte iz celog životnog ciklusa.

***Ključne reči**: životni ciklus, ambalaža, polimeri, biopolimeri.*

INTRODUCTION

The term "life cycle" refers to the main activities during the life cycle of the packaging from its production, including raw materials, distribution, (re)use and maintenance, recycling, and final disposal (*Wolfson et al., 2019*). The Life Cycle Assessment (LCA) includes gathering information on inputs and outputs of processes such as emissions, waste, and resources and translating them into environmental impact factors (using impact assessment methodology), such as contributing to climate change, eutrophication, acidification, and toxicity to humans and the ecosystem (*Yates and Barlow, 2013*). LCA presents a systematic approach to address environmental issues and includes four phases (*Hottle et al., 2013*):

1. Goal and scope definition ("Goal and Scope Definition"). In this phase the boundaries of the observed system are established, the processes to be analyzed, which methods for impact analysis will be applied and which categories of impact will be analyzed. This phase is probably the most critical because in some cases the application area will require different approaches, where it is not appropriate to include all phases of the life cycle. One example is the production of granulated polymers, which can have numerous uses, so it becomes impossible to monitor numerous life cycles after production. The functional unit, one of the most important elements of the LCA study, is defined precisely in this phase. It represents a quantitative measure of the output of a product or service delivered by the system (*Azapagić et al., 2003*).

2. Inventory analyses ("Life Cycle Inventory"). In this phase, the system is defined as a set of material and energy-related operations. A system is also separated from its environment by system boundaries and it is divided into several interconnected sub-systems, which may consist of a single operating unit or a group of operating units. Each sub-system must be defined in detail through the input of materials and energy, up to the emission of gases and solid waste of such a sub-system (Azapagić et al., 2003). In this phase, the quantities of materials, energy, and chemicals that enter the production process as well

as the emission of harmful substances into the air, water, and soil are defined. In addition, the effects of radiation and land occupation can be analyzed.

3. Life Cycle Impact Assessment (LCIA) phase. In the third phase, the impact assessment is performed on categories such as global warming, increasing soil and water acidity, reducing fossil fuel stocks, etc. In the first step of this phase, characterization is performed, ie impacts are calculated based on LCI data. In the next step, normalization is performed, where all influences are reduced to the same unit, and then each influence is assigned a weighting factor depending on the relative importance of that influence.

4. Interpretation. This is a systematic process for identifying, verifying, qualifying, and evaluating information and non-compliances obtained from life cycle inventory analysis results, as well as final recommendations. This phase is the most important in the whole analysis because it can be used to answer what has the greatest impact on one of the categories. Interpretation is a phase intended for system improvement and innovation.

LIFE CYCLE ASSESSMENT STANDARDIZATION

LCA is a quantitative application of the concept of life cycle thinking (LCT) and is based on the evaluation of the life cycle of a product or service from the aspect of environmental protection (*Flanigan et al., 2013*). In order to relativize the impact of products on the environment, ISO introduces the 14000 series of standards that deal exclusively with this topic, with a special place being taken by the LCA life cycle analysis. The ISO 14000 standards include the environmental management system and the environmental management life cycle assessment. Thanks to this framework, the entire LCA procedure is divided into four characteristic phases (ISO 14040:2006 and ISO 14044:2006):

- Defining the goal and scope;
- Inventory analysis;
- Impact assessment;
- Interpretation.

The use of ISO 14040 standards in polymer production industries, as well as accurate goal and scope definition, inventory data, impact assessment, and interpretation, leads to the advancement of new technologies for the development of sustainable polymers globally (*Ramesh and Vinodh, 2020*).

Relevant impact categories commonly reported as an LCA studies results are (*Tamburini et al., 2021*): Global warming potential (GWP), Ozone depletion potential (ODP), Acidification of soil and water potential (AP), Eutrophication potential (EP), Photochemical ozone formation potential (POFP), Fossil fuels depletion potential (FDP), Human toxicity potential (HTP), Eco-toxicity potential (ETP), Water depletion potential (WD), Land occupation potential (LOP), etc.

POLYMER LIFE CYCLE ASSESSMENT

Recent data point to an increase in polymer materials consumption and, as a result, plastic waste. Global plastic output hit 338 million tons in 2019, representing a 640% growth since 1975 (Matthews et al., 2021). Polymer packaging materials are the most popular in the international packaging market for a variety of reasons: strength, flexibility, workability, the ability to combine with other materials, and low cost. Some LCA analyses were performed only on examples of polymeric materials:

Grigale et al. (2010) presented a life cycle analysis of polyethylene (PE). PE life cycle analysis indicates the possibility of resource recovery through recycling and incineration. Total energy for PE production was 76 MJ/kg, mass 0,2 kg/FU (functional unit), energy 15,2 MJ/FU, emission GHG 4,8 kg CO2eqv/kg, GHG emission 0,96 kg CO2eqv/FU.

The Life Cycle Assessment of Polyethylene Terephthalate Packaging (PET) was briefly overviewed by Gomes et al. (2019). PET bottles were compared to traditional systems like glass bottles and metal cans in this scenario. PET outperformed these two options in terms of environmental performance, making it the ideal option for carbonated beverages. The general goal was to point to technologies for producing PET that have a lower environmental impact and can be recovered more efficiently, such as closed-cycle recycling.

When using composite materials (multilayer materials made of polymers and aluminum or paper) versus monomaterials, an LCA study showed that composite packaging has a larger environmental impact than plastic packaging. Furthermore, with the exception of disposal, the environmental effect of raw material extraction is the largest of all life cycle stages. The environmental impact of composite packaging is primarily due to fossil fuels, land use, and respiratory inorganics, whereas the impact of plastic packaging is primarily due to fossil fuels. However, because composite packaging has not been properly recycled and reused, it has a bigger environmental impact. By creating technology to extract polyethylene and aluminum from packaging, this environmental impact could be reduced (Xie et al., 2011).

BIOPOLYMER LIFE CYCLE ASSESSMENT

Biopolymers are biodegradable so might be composted rather than discarded or recycled, completing the natural carbon cycle, which is their advantage over polymer materials. They can be obtained directly from natural sources, such as cellulose, starch, or sucrose, through fermentation and chemical synthesis using renewable biological monomers, or directly produced by bacterial cultures as polyhydroxyalkanoates and polyhydroxybutyrate. However, global bioplastic output is still less than 1% of total plastic production, owing to the fact that research and development costs still account for a significant (*Tamburini et al., 2021*). Most LCA studies have been conducted poly(lacticacid) (PLA), the poly(hydroxyalkanoates) (PHAs), and starch-based materials.

Because degradation causes global warming and climate change, bioplastics composting is a viable alternative to landfilling. Biopolymers are being designed with features such as biodegradability and composability. Bioplastics composting may be more effective than incineration since industrial composting has a lower environmental impact (*Weiss et al., 2012*).

POLYMER VS BIOPOLYMER LIFE CYCLE ASSESSMENT

A large number of LCA studies have been performed comparing the effects of commercial packaging materials with new biopolymer materials. Although biopolymer technologies are new and have been compared to optimized commercial technologies, biopolymers are environmentally friendlier compared to fossil-based polymers offering important environmental benefits (*Patel et al., 2003; Ramesh and Vinodh, 2020)*. Most bio-based polymers produce better outcomes in terms of the usage of fossil fuels and GHG emissions. One exception is the landfilling of biodegradable polymers, which, if landfill gas isn't caught, can produce methane emissions, potentially making the system unappealing for lowering greenhouse gas emissions (*Patel et al., 2003*).

This observation is based on a limited number of reviewed articles since the results may vary depending on the methodological assumptions (e.g., how the authors addressed the issue of carbon uptake by biomass and the subsequent release of the biogenic carbon during use and end-of-life (Nikolić et al., 2015)), a technique used to solve the problem of multifunctionality, ie. the chosen allocation approach (Morão and De Bie, 2019) and the consideration of land use change related impacts associated with the production of the biomass feedstocks (Morão and De Bie, 2019). The most important conclusions of the LCA studies are shown in Table 1.

Table 1. LCA comparative studies for polymer and biopolymer materials

Materials	Conclusions	Reference
PLA/PP	Analysis of inventory for production and disposal requires higher energy consumption for PP (3261 MJ/t) compared to PLA (2225 MJ/t). Greenhouse gas emissions from production and disposal are very similar for both tested materials.	*Bohlmann, 2004*
PHA/PP	Air emissions at the landfill for conventional plastics were significantly higher for all tested gases except methane. In the case of incineration, air emissions were higher for bioplastics in the case of CO_2, CH_4, NO_x, SO_x, but less for HCl and HF.	*Khoo and Tan, 2010*
PLA, TPS, PHA/HDPE, LDPE, PET, PP, PS	In CO_2 emission, PS and PET showed the highest level of impact. Impacts for PLA in eutrophication, ozone depletion, and ecotoxicity are significantly higher than the other five polymers.	*Hottle et al., 2017*
PLA/PS	PLA trays had a higher impact than PS trays for all impact categories, except in Resources and NREU. It was found that 8.98 g was for one PS tray and 11.36 g is needed for PLA trays and the Total damage of PLA granules was lesser than the Transport of PLA and rises GW significantly. PLA manufactured process had a lesser impact than PS granules.	*Ingrao et al., 2017*
PLA/PET	The findings revealed that the true advantage of PLA bottles over PET bottles comes from the use of renewable resources, but that this benefit comes at a cost in terms of environmental impact due to the higher impact on human health and ecosystem quality (due to the pesticides usage, land and water consumption for the production of raw materials). PLA products also had lower NREU and GWP than the petrochemical polymer products.	*Gironi and Piemonte, 2010*
biobased HDPE/fossil HDPE	This study shows a reduction of impact of around 60% for both climate change and fossil fuel depletion categories when using biobased HDPE instead of its fossil counterpart. For all other impact categories, fossil HDPE achieves better results than the biobased product.	*Belboom and Léonard, 2016*
PLA/PET	An LCA comparison of PLA and PET bottles revealed that the biomass-based option is better in terms of net GWP and cumulative energy usage (CED). When PLA granules are used instead of PET granules in bottle manufacturing, the net GWP and CED of the bottles are reduced by 30.9 %t and 9.7 %, respectively. However, if no credits are given for atmospheric CO_2 fixed by corn, and the energy in corn feedstock is accounted for, the PLA benefits would be greatly reduced.	*Nikolić et al., 2015*
PLA/PP, PET	The biggest environmental hotspot for PLA cups was identified as the process energy used in the conversion from biomass to PLA polymer, followed by the electricity consumption of thermoforming the cups. The biomass acquisition step was discovered to have a minor overall influence. PLA cups outperform PET cups in terms of climate change mitigation (22 % lower impact) and fossil resource depletion (52 % lower) when compared to both PET and PP cups (41 % lower). PLA cups, on the other hand, have much greater consequences on photochemical ozone production, acidification, and terrestrial eutrophication than PET and PP cups. PP cups have better performance than PET cups.	*Moretti et al., 2021*

* PLA – polylactic acid; PP – polypropylene; PHA – polyhydroxyalkanoates; TPS – thermoplastic starch; HDPE – high density polypropylene; LDPE – low density polypropylene; PET – polyethylene terephthalate; PS – polystyrene; NREU – non- renewable energy use; GWP – Global Warming Potential; CED - cumulative energy demand.

CONCLUSION

Packaging life cycle assessment is a young scientific discipline that begins with the acceptance of the fact that manufacturers and products or packaging users have a responsibility for their impact on the environment. Earlier, it was considered that the cycle begins when the material in the form of raw materials is delivered to the factory and ends when the finished product "comes out" of the factory and reaches the consumer. Today, packaging is increasingly managed in accordance with legal regulations. LCA, also, enables manufacturers to choose clean production techniques with fewer hazards and harmful materials, as well as improve energy efficiency, waste management, and recycling.

From an environmental perspective, it is impossible to make a correct general conclusion about whether biopolymers should be preferred contrary to petrochemical polymers. Despite the fact that there is a growing corpus of life cycle assessment (LCA) research on (bio)polymers, comparisons between studies and pooling of general results have been difficult by uneven methodology and assumptions. To produce reliable data, with the aim to evaluate and compare the environmental performance of various bio(polymers), it is required to harmonize the prior research and to conduct further LCA research with more reliable and uniform data collection over the entire productive system.

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