The Importance of Biopolymer life Cycle Analysis

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Abstract— **Modern society is turning more and more towards sustainable development and requires the producers of new materials to switch to natural products. Biodegradable polymers are degradable plastics where decomposition takes place under the influence of microorganisms found in nature, such as bacteria, fungi and algae. In order to assess the ecological suitability of biopolymers, an LCA life cycle analysis is carried out. Life cycle analysis (LCA) is an analytical tool used as a framework for analyzing the impact of any product or process on the environment. Also, there is a need for an integrated waste management system. Life Cycle Assessment (LCA) represents a quantitative application of the concept of life cycle thinking (LCT), and it is based on the evaluation of the life cycle of a product or service from the aspect of environmental protection. The importance of LCA itself has been recognized by international agencies, which is why the ISO 14000 series of environmental protection standards was formed, including the environmental protection system management standard 14001 and environmental protection management - life cycle assessment, ISO 14040 series. The aim of this paper is to show the importance and way of performing product life cycle analysis as well as the problems encountered by scientists who deal with it.**

Index Terms— **biopolymers; life cycle analysis; life cycle thinking; waste management; ISO standards.**

I. Introduction

Advances in science and technology have led to the rapid development of modern society, which has undoubtedly led to excessive consumption and even complete exploitation of some natural resources. The energy and materials needed for the sustainable growth and development of the human population are obtained to the greatest extent from non-renewable fossil sources. The production, transport and use of energy greatly affect the environment in which we live. In the case of energy, this impact is mostly negative and refers to direct environmental disasters, acid rain and even global warming [1]. Thanks to technical and technological prosperity, there is a significant increase in the production and consumption of polymers, synthesized from monomers obtained from oil processing. According to some forecasts, the production and consumption of oil and gas should reach a maximum from 2030 to 2050, after which it would gradually begin to decline, which could result in a global energy crisis [2]. Biopolymers are considered new and modern materials even though they have been in use for a very long time. Modern industrial use of organic macromolecular materials began around 1850 [3]. Whether all polymer materials used today are in accordance with the principles of sustainable development is a very complex question. For this reason, they switched to the synthesis of biomaterials, but it is still necessary to use certain methods and techniques that deal with the study of the impact of materials on the environment [4]. In order to assess the ecological suitability of biopolymers, an LCA life cycle analysis is carried out. Life cycle analysis (LCA) is an analytical tool that sets a framework for analyzing the impact of any product or process on the environment [5]. There is also a need for an integrated waste management system, which would contribute to more efficient use, recycling and disposal of biopolymer materials [6]. When assessing the ecological suitability of individual packaging materials, an approach of balancing positive and negative aspects is necessary. Life cycle analysis is a calculation process, during which all consumption (inputs) and all emissions (outputs) during the life cycle of a certain packaging material are analyzed and summarized. During the assessment, energy consumption, emissions into water and air, as well as generated solid waste are evaluated. The basic methodology consists of disassembling the defined system into components, i.e. process steps, and measuring the mass and energy balance for each separate process step. The summarized results are displayed via eco points, or multifunctional indices. The ultimate goal of life cycle analysis is to reduce environmental impact [7].

The aim of this paper is to show the importance and method of performing product life cycle analysis as well as the problems encountered by scientists who deal with it.

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II. POLYMER MATERIALS

Polymers are organic or inorganic compounds built from molecules of large molecular masses (macromolecules) in which atomic groups, the so-called "structural units", connected by chemical bonds thus forming a polymer (macromolecular) chain. In a narrower sense, the term polymers are considered only those macromolecules that are made up of only one or several (two to three) types of repeating structural units. Reactions polymerization and polycondensation molecules, monomers are bound into a macromolecule. The properties of polymer materials are determined by the type of monomer, methods and conditions of polymerization, molecular structure of the polymer, type and amount of additives [8]. Along with all polymers, biodegradable ones were also developed, which resulted in

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their acceptance by the ASTM and ISO organizations in July 2000. Their standardization was carried out and mass controlled production began. Biodegradable polymers are degradable plastics where decomposition takes place under the influence of microorganisms found in nature, such as bacteria, fungi and algae. This is the original definition of biodegradable polymers. It has been developed for years, and no new polymer can be certified if it does not meet every item prescribed by the predetermined standard [6,9].

Every discussion about polymer chemistry starts from the question of whether the polymer is of natural origin or synthesized, that is, the question of whether it is possible to restore the source of the polymer or not. Biodegradable polymers can be of natural origin and synthesized, from renewable and non-renewable sources. For example, natural biopolymers are produced by growing certain crops, which may involve the use of artificial fertilizers, herbicides or pesticides that have significant effects on the soil if not used properly. Almost every biodegradable polymer is not taken directly from nature, but is extracted from raw materials and then purified. These processes may require the use of certain chemical agents, water, energy. Justification, both monetary and environmental, are an inevitable factor in the production of any polymer, as well as any product [9]. Degradation of polymers is certainly one of the aspects of environmental protection on which special emphasis is placed. This phenomenon is defined as a change in the initial characteristics of polymer materials, such as: stretchability, color, shape, etc.; under the influence of one or more natural factors such as: heat, light or various chemicals [5]. Most of today's polymers contain various additives to stabilize or destabilize the material. Additives that were used before had the role of reducing the impact of the environment on the packaging and affecting the extension of the shelf life of the packaging. Newer types of additives are applied to enable the splitting of polymers into smaller constituents, which are more favorable for degradation [10].

III. BIODEGRADABILITY OF POLYMERS

Research results show that biomass as a renewable raw material is the only serious alternative to oil. As a product of biosynthesis, 170-200 billion tons of biomass is produced annually on earth, which is practically within reach. Of the total amount of biomass, which plants annually synthesize, people have so far used only 6 billion tons, that is, only 2-3% [11]. Because of all this, one of the growing trends of the chemical industry is certainly the production of bio-polymers. The advantage of bio-polymers compared to other materials can mostly be seen from the aspect of environmental protection, because such materials are produced from renewable sources, and after disposal they are subject to biodegradability or can be composted [9]. In the literature, the terms biodegradable and bio-polymers are often equated, although there is one essential difference between them. Biodegradable polymers are materials whose physical and chemical characteristics are subject to decomposition, during which their complete decomposition occurs thanks to the action of various microorganisms. Bio-polymers or bio-based polymers can be biodegradable (eg polylactic acid) or non-degradable (eg bio-polyethylene). In addition, as most bio-polymers are biodegradable, there are also biodegradable polymers that are not bio-based [12]. According to the ASTM standard D-5488-94d and the European standard EN 13432, the term "biodegradable" means: "capable of undergoing decomposition or degradation to carbon dioxide, methane, water, inorganic components and biomass" [13]. When talking about bioremediation, one comes across another term that plays an important role, especially in waste management, and that is compostability. In short, compostability represents the biodegradability of the product with the use of a suitable medium [12, 13]. Also, composting is done under controlled conditions, such as elevated temperature and humidity. The basic feature of biopolymers is their biodegradability. Conventional biopolymers are not biodegradable because they have very long chains of molecules that are too large and too interconnected to be degraded by microorganisms. Unlike these, polymers made from natural plant substances have molecules that are degradable by microorganisms. In order for them to be degradable, there must be at least one enzyme in the biosphere that accelerates the degradation of the chemical chain of the given polymer [14, 15]. There are many standards that define a method for measuring the biodegradability of a substance, with each country having its own standards. Requirements regarding the degree of degradation vary from 90 to 60% degradation of the substance in a time period of 60 to 180 days from the moment of placing the substance in an environment suitable for composting [16].

Biomaterials (biopolymers) are polymers produced from renewable sources. Unlike conventional polymers, which are produced from non-renewable sources (coal, oil), biopolymers are produced from vegetable raw materials, first of all, and more recently from animal raw materials. Production from renewable sources can be a significant contribution in terms of lower energy consumption during production and a wider range of waste disposal methods, with a minor impact on the environment. The quality of bioplastic products is evaluated not only by biodegradability but also by the functionality of the product. A biodegradable product is useless if it cannot meet the requirements set before it in the form of mechanical and chemical resistance, durability, etc. That is why it is very important that bioplastics manufacturers focus not only on the biodegradability of the material but also on other properties of the polymer so that the new polymers are competitive with conventional polymers [14-16].

IV. IMPORTANCE OF PRODUCT LIFE CYCLE MONITORING

The life cycle represents the very core of the sustainable development of products and materials. As its name suggests, it deals with the monitoring of the entire supply chain, from the production of raw materials through processing, all the way to waste management after product use. Observing the product in this way, it becomes possible to form a complete picture of human interaction with nature, where it is easier to see the places where it is necessary to make corrections in accordance with the principles of sustainable development.

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This concept is also called Life Cycle Thinking (LCT), which indicates the connection of each phase of a product's life with environmental protection [10]. The scheme of LCA is given on Figure 1.

Fig. 1. LCA scheme [17]

The concept of life cycle thinking is based on the evaluation of the product's impact on the economic, social and environmental aspects of sustainable development. Adopting this kind of thinking concept can provide insight into business actions that have been taken to approach the concept of sustainable development, in the way of evaluating the outcome of the actions taken, i.e. whether the actions had an effect on the improvement of the system's characteristics, without shifting or transferring the problem to another segment. LCT is made up of several applications (tools), such as: life cycle assessment (environmental protection), life cycle costing (economy) and social cycle assessment (society) [18]. Life Cycle Assessment (LCA) represents 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 [18, 19]. The ISO 14000 series of standards deals with environmental protection, and includes the environmental protection system management standard 14001 and environmental protection management - life cycle assessment, series ISO 14040. The LCA work method is structured through a widely adopted form, achieved by international consensus, which is in the form of ISO standards.

Thanks to this framework, the entire LCA procedure is divided into four characteristic phases [20]:

- Defining the goal and scope of application (ISO 14041);
- Inventory analysis (ISO 14041);
- Impact assessment (ISO 14042);
- Interpretation (ISO 14043).

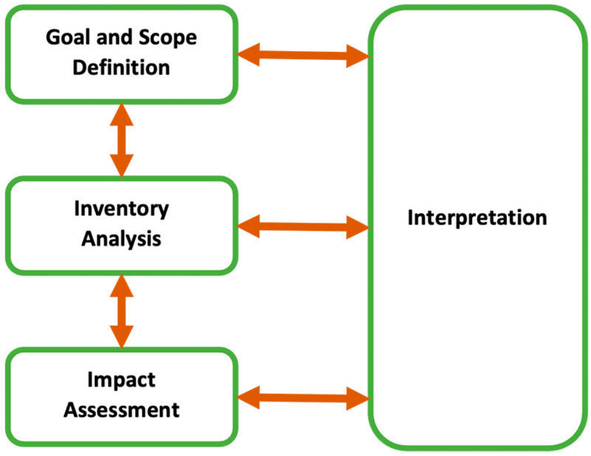

Fig. 2. LCA framework [21]

Defining the goal and the area of application represents the initial phase of the preparation of the entire LCA document. The goal of the study is formulated on the basis of exact questions, target group and intended application, while the field of application defines the system and its limitations from the temporal, geographical and technological aspects. 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 [10]. Analysis of the life cycle inventory - Life Cycle Inventory (LCI) represents a quantitative description of the entire system, which is why it represents the most objective phase of LCA.

Inventory analysis consists of

- Additional definitions of the system and its limitations;
- System flow diagrams;
- Database;
- Environmental load allocations;
- Calculations and report results [10].

In this phase, the system is defined as a set of material and energy-related operations, such as: production process, transport process or fuel extraction process. A system is also separated from its environment by system boundaries. The system is divided into several interconnected sub-systems, and may consist of one operating unit or a group of operating units. It is necessary to define each subsystem in detail through the input of materials and energy, up to the emission of gases and solid waste of such a subsystem [22]. All inputs and outputs are in balance and the database is formed, taking into account the output unit of each subsystem. On the basis of statistics formed for a certain period of time, environmental burdens are defined as the consumption of resources and the emission of gases and/or solid waste. Environmental burdens include the consumption of fossil fuels, the emission of sulfur

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dioxide, the amount of solid waste, and the like, and are calculated using the formula [22].

$$B_k = \sum_{i=1}^{I} bc_{k,i} x_i \quad k = 1,2, \dots K \tag{1}$$

Where $bc_{k,i}$ – the load k is related to the flow of material or energy x_i, during the activity process. An example could be the CO2 emission (load $bc_{k,i}$) realized per ton of natural gas (material flow x_i), for the production of electricity (process or activity).

The inventory analysis also includes the allocation of the environmental load, which can be a problem with multi-functional systems, such as for example a co-production system, waste treatment or recycling. Allocation represents the determination of the environmental load by products or functional outputs individually [22]. Assessment of the impact of environmental load based on inventory analysis represents quantitative and qualitative procedures that characterize the impact of the system. At the very beginning, loads are grouped into individual categories, which have a potentially bad impact on the environment or human health, as well as on the consumption of natural resources. The categories are formed in such a way that one load category can connect several individual impacts.

The most common impacts mentioned during LCA are:

- Consumption of resources;
- Global warming;
- Damage to the ozone layer;
- Acidification;
- Eutrophication;
- Photochemical smog;
- Toxicity to humans;
- Water toxicity [20, 22].

In the problem-oriented approach, the impact is calculated in relation to the reference substance. In general, the impact is calculated using the formula:

$$E_i = \sum_{k=1}^{K} bc_{I,k} B_k \quad I = 1,2, \dots L \tag{2}$$

Where E_i is the influence, while $bc_{I,K}$ represents the relative contribution of the load Bk. Although the number of impact categories is significantly smaller than the total number of identified loads, it is significant in the sense that comparisons between different system impacts are possible. To facilitate decision-making, impacts are classified according to importance, which is called valuation. The task of evaluation is to present several different impact categories with a single number, which is denoted as EI, and is calculated according to the formula [22].

$$EI = \sum_{I=1}^{L} w_I E_I \tag{3}$$

Where w_I is the relative importance of the influence of EI. Each influence can be represented by a number on a scale from 1 to 10, which in itself indicates the importance of an individual influence in relation to other influences. The higher the numerical score, the greater the significance of the impact, which can help when making decisions.

Interpretation is a phase intended for system improvement and innovation. It includes steps such as: identification of key burdens and impacts, identification of life cycle phases that contribute most to these impacts (so-called "hot spots"), evaluation of these findings, sensitivity analysis for data quality and non-compliance, as well as final recommendations [19-22].

V. CONCLUSION

People's awareness of sustainable development has contributed to many things changing for the better in terms of preserving the environment and what nature has given us. The human influence in all of this is very large, and in terms of the materials industry, especially polymer materials, there has been a major shift towards the replacement of harder-to-degrade polymer materials with biopolymers. Biodegradable materials have become in demand on the packaging market, and research leads in the direction of improving the functional properties of biopolymers. In order to relativize the impact of products on the environment, ISO introduced the 14000 series of standards that deal exclusively with this topic, where the LCA life cycle analysis occupies a special place. The idea of biodegradable polymers from renewable sources is to close the natural cycle, where the end of one cycle marks the beginning of the next cycle. The biggest problem of LCAs carried out in different researches was the selectivity of the impact, where only certain categories were processed. Another problem was the heterogeneity of the data, as some studies focused on individual segments of the analysis, while some related to all aspects of the process. Future research should be conducted using standardized methods, in order to avoid exposing representative segments of the process. Also, in addition to the standardized test methods and agreed limits of the LCA analysis system, it would be possible to individually interpret the results in the desired direction through the impact categories. The subjective impression is that the issue of environmental protection in the field of packaging is strongly stimulated by circumstances, caused by the increased interest of consumers. However, the real picture of the impact of individual materials on the environment will have to wait for some time.

Despite all the aggravating factors, it is important that the consciousness of consumers and producers has changed to some extent so that they can understand the negative impacts they themselves make on the environment, which belongs to everyone equally. In the underdeveloped areas of the planet, there is still little talk of life cycle analysis in general, but with a change in consciousness at a lower level, a change on a global level can be expected in the near future. That is why it is very important that the analyzes carried out are relevant and performed using standardized methods so that they can be used on a global level.

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