

Life cycle assessment of beverage bottles

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Abstract. Poland ranks sixth in Europe (behind Germany, Italy, France, Spain and England) in terms of demand for plastics, and the Polish plastics processing industry used in 2017 to produce about 3.5 million tons of polymer materials, in view of total demand in Europe estimated at approx. 51.5 million tons. It is assumed that Polish industry uses about 7% of total demand in Europe. In Poland, about 33% of the domestic demand for plastics is directed to the packaging industry. Along with the growing demand for plastics, packaging production and social consumption are increasing. The article presents the sources of greenhouse gas emissions from the food industry. An LCA (Life Cycle Assessment) analysis was carried out that identifies potential environmental burdens for the bottle forming process. The scope of work included selected stages of shaping bottles made of two types of PET and PLA polymer materials. The aim of the work was to demonstrate the impact of bottle production on the condition of the natural environment and to indicate the factors determining these influences.

1. Introduction

Climate change is currently one of the most important and complex problems in the field of environmental sciences [1]. The fight against climate change is nearly 40 years old. Already in the seventies of the last century the hypothesis was raised that the increase in CO₂ concentration may have an impact on the climate. Therefore, in 1979, the First World Climate Conference was convened in Geneva. It was then established under the auspices of the World Meteorological Organization (WMO), the United Nations Environment Program (UNEP) and the International Science Council, the World Climate Program. Countries have also been called on to prepare for global climate change and related threats [2]. Carbon dioxide emissions caused by burning fossil fuels are the most important cause of global warming and global climate change. Greenhouse gas emissions worldwide account for 76% of CO₂ emissions.

A typical PET bottle is a major threat to the natural environment due to emissions of large quantities of compounds, its further use and disposal. It is estimated that about 4% of crude oil in 2016 was intended for its production. In addition, bottles are a real threat due to the increasing amount of waste. It is estimated that approximately 7.2–14.1 million tonnes of plastic waste disposed of in landfills each year represents 22–43% of waste landfilled. Most plastics are not biodegradable, and therefore most of the polymers produced will last for decades, centuries and probably millennia [3].

Polylactic acid (PLA), a plastic substitute made of fermented vegetable starch (usually corn), has quickly become a popular alternative to traditional petroleum-based plastics. Over time, more and more countries and countries are following in the footsteps of China, Ireland, South Africa, Uganda and San Francisco calling for a ban on the use of plastic shopping bags responsible for so many so-



called "white contaminants" around the world. PLA, which is a natural resource, is an excellent biodegradable replacement. Proponents also tout the use of PLA, which is technically 'carbon neutral' because it comes from renewable, carbon-absorbing plants - as another way to reduce greenhouse gas emissions in a rapidly warming world [2], [4], [5].

Bearing in mind the rapidly progressing industrialization and the resulting degradation of the Earth's natural environment, more and more supporters gain the idea of sustainable development and pro-environmental consumption. They result in in-depth studies on the possible impact of human products - technical objects, and in particular machines and devices on the environment. At the same time, due to the growing interest in environmental issues, there is a need to evaluate the environmental impact of technological processes, for example by quantifying the environmental burdens they generate. Although the production process of PET bottles started in the mid-1970s, they appeared on the Polish market only at the turn of 1989/1990 along with economic changes and the opening of the market. Currently, PET is the main packaging material used in the food industry for the production of various types of bottles, jars and containers. It is estimated that in 2016, the Polish plastics processing industry used approx. 3.3 million different polymer materials, which means an increase of approx. 6.9% compared to 2015. Demand for plastics in Europe in 2016 is estimated at about 50.5 million tons, which means an increase of 3.2 million tons compared to 2015. Opportunities and the potential of the industry in Poland illustrates the demand for plastics from plastics processing companies per conversion 1 inhabitant. It is currently around 85 kg, while the EU average is over 95 kg. The relation between the quantities of plastics processed into products and the generated waste amounts to about 3 million tons of processed plastics, which generate about 1.5 million tons of waste, 25% of which is recycled, and 19% is used for energy recovery [1].

The problem of improper use of plastic waste affects not only land but also the marine environment. The vast majority of waste in rivers and seas gets there due to inadequate waste management on land and people littering the environment. The huge garbage island, located in the north of the Pacific Northwest of Hawaii, is one of the most evident proofs of the destructive activity of man. It is estimated that at the moment it covers an area of about 1.6 million square kilometers, which is five times as much as the area of our country. The danger of plastics occurring in the aquatic environment is not only a long-term process of their decomposition, but above all a real threat to all living organisms.

For the sake of the natural environment it is recommended to adopt appropriate pro-environmental attitudes. From an ecological point of view, packaging should have, among others, the following features: minimizing the consumption of raw materials and energy during the production process; low level of water, soil and air pollution at the stage of the process of production, use and waste management; characterized by the lowest possible mass, because then they occupy less space during storage and transport; generate as little waste as possible (both by weight and by volume) and belong to the applicable organizational and legal system by using clear and unified ecological marks. World food corporations have long been interested in biodegradable plastics, noting in them the possibility of reducing CO₂ emissions and adjusting production to environmental standards. Among the many available materials, one should distinguish a biodegradable polymer obtained from vegetable pulp used for packaging production. Polylactic acid itself, polylactic acid, polylactic acid, PLA, is a biodegradable polymer obtained from corn. This is a biodegradable plastic in the natural environment and is absorbed by living organisms (bacteria), so it is an environmentally biodegradable biodegradable polymer. they need heat, bacteria and high humidity for decomposition, in which case the bottle and the label are decomposed into organic matter, water and carbon dioxide.

PLA bottles are produced in a technology similar to that for PET bottles. Preforms are produced from the polymer, which are then blown into bottles. For the production of preforms, the 24-socket HyPET 120 system is used, which produces preforms for 1 liter, 0.5 liter and 0.33 liter bottles. Blowing the bottles is done on a 10-slot BLOMAX-10 machine. The bottles are biodegradable within 75-80 days under commercial composting conditions. The most environmentally friendly are

biodegradable packaging produced from renewable natural resources annually, which after use can be recycled organically – composting [6-8].

The purpose of the work is to determine the impact of environmental damage resulting from selected production operations carried out for the process of shaping disposable bottles for beverages made of biodegradable and non-biodegradable plastics.

2. Methods

Usually a set of international standards from the International Organization for Standardization (ISO) was used as a guideline for systematic approach and testing. The framework for this study was determined in accordance with the guidelines of ISO 14040 standards. The purpose and scope of the problem definition and inventory analysis were formulated and carried out in accordance with the recommendations of the ISO 14040 series standards. LCA and interpretation were carried out in accordance with ISO 14044 respectively, and ISO 14049 was used to develop functions, distinguish functions of comparative systems, establishing input and output data of unit processes and system boundaries [9]. There are four phases of life cycle assessment: goal and scope determination, set analysis (data inventory), impact assessment, interpretation [10]. Ecological life cycle assessment is about verifying and estimating related ones with the organization of environmental burdens. Areas related to the entire production process are assessed. The potential impacts of these burdens are estimated and ways to reduce them are identified. In order to conduct the tests, the IMPACT 2002+ method was used, which was a combination of four LCIA methods: IMPACT 2002+, Ecoindicator 99/E, CML and IPCC using the SimaPro TM version 8.4.0 program. Ecoinvent version 3.3 was used as the database. A feature of this method is the fact that the identified categories of impact (emission of carcinogens, emission of non-carcinogens, emission of inorganic substances causing respiratory diseases, ionizing radiation, ozone depletion, emission of organic substances causing respiratory diseases, poisoning of water resources with toxic substances, poisoning of soil resources) toxic substances, acidification / poisoning of soil resources, land use and degradation, acidification of water resources, eutrophication of water resources, greenhouse potential, energy produced from non-renewable sources, depletion of mineral resources) are then grouped into four categories of damage such as human health, quality of ecosystems, climate change, depletion of resources [11], [12]. Because Impact 2002+ is a combined method, it was used to estimate emissions of carbon dioxide, sulfur oxides, nitrogen oxides, ammonia, sulfur (IV) oxides and carbon monoxide into the air [13]. Developed by the International Climate Change Team (IPCC), the IPCC (carbon footprint) method is used to demonstrate the impact of products on greenhouse gas emissions. The IPCC method allows quantitative assessment of the impact of individual greenhouse gases (GHG) on the greenhouse effect, in relation to CO₂, in the adopted time horizon of 100 years. The greenhouse effect assessment index related to carbon dioxide is 1 (GHG = 1) [14-16].

In the case of an environmental impact assessment, 1000 units of 500 ml bottles were used as the functional unit. Collection analysis in the life cycle consists of collecting data and selecting calculation procedures, determines the inputs and outputs for the tested product during its life cycle [17]. As the system boundary, raw material intake to the preheating furnace and the pre-blow process, specific blow-out, degassing and bottle cooling were adopted. Raw material production, transport and utilization remain outside the system boundaries [18], [19].

3. Results and discussion

Results of environmental damage burdens for the process of heating preforms made of PET and PLA are presented in Table 1. When making a comparative analysis of environmental loads, it should be stated that a bottle made of non-biodegradable material causes twice as much environmental damage taking into account negative impacts on ecosystem quality, climate change, depletion of raw materials and human health.

Table 1. The results of the damage category for heating process

Damage categories	Heating of PLA preforms	Heating of PET preforms
Ecosystem quality (Pt)	0.001138419	0.000172634
Climate change (Pt)	0.000524541	0.001465995
Resources (Pt)	0.000441035	0.002352974
Human health (Pt)	0.000960264	0.00394323

Results of environmental damage loads for the stretching process and extension of preforms made of PET and PLA are presented in Table 2. The result of the comparative analyzes is the statement with comparable environmental loads as a result of the stretching and heating process of the analyzed preforms.

Table 2. The results of the damage category for stretching process

Damage categories	Stretching the PLA preform	Stretching the PET preform
Ecosystem quality (Pt)	0.000824556	0.001155996
Climate change (Pt)	0.000171777	6.4468E-05
Resources (Pt)	0.000547814	0.00065242
Human health (Pt)	0.000483941	0.000696379

Figure 1 presents profiles of environmental influences for the process of heating the raw material. In the scope of these interactions, the dominance of the PET preform heating stage over the pre-heating stage of the PLA preform is visible. The main burdens are related to the depletion of fossil fuel resources, which have a significant impact on the depletion of raw materials. It is connected with acquiring energy resources from non-renewable sources. Environmental influences are mainly related to the acquisition of raw materials used for the production of fuels, mainly hard coal, which in Poland is the basis of the energy system.

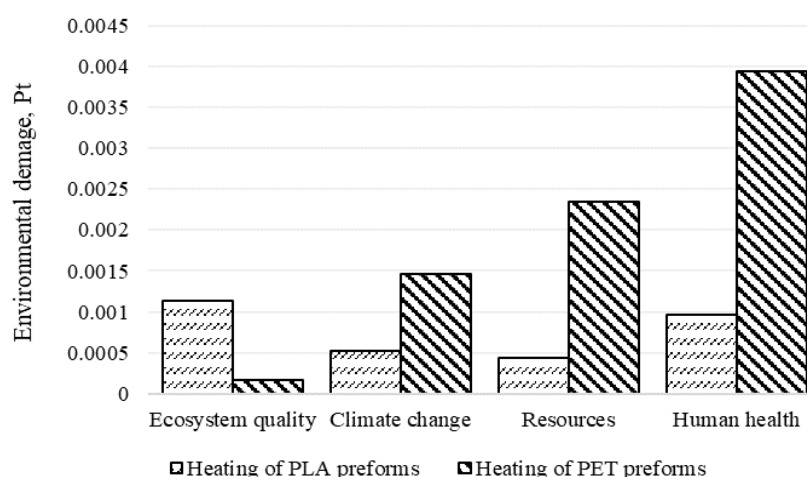
**Figure 1.** Test results for the preform heating process obtained for specific environmental damage expressed in environmental points, Pt

Figure 2 presents profiles of environmental impacts in environmental points, from which it is clear that the non-biodegradable material applied, by as much as 20 percentage points outperforms

biodegradable material in the category of human health. In addition, the associated impacts were also noted with depletion of fossil fuel resources.

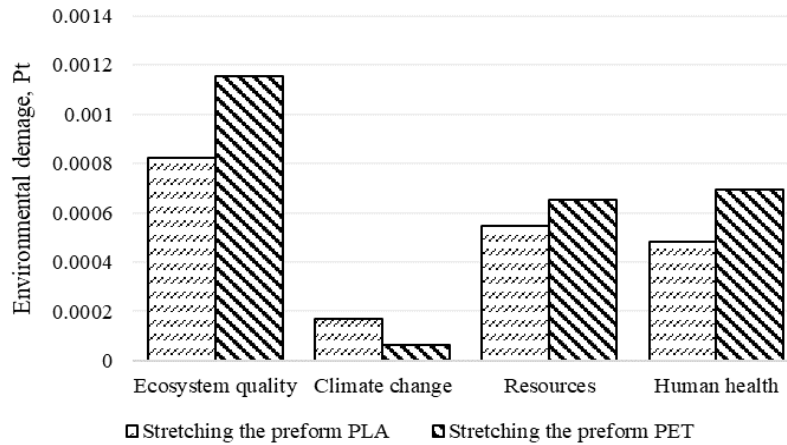


Figure 2. Test results of preform stretching process obtained for specific environmental damage expressed in environmental points, Pt

Sources of gas emissions for all the mentioned bottle shaping stages are shown in Table 3-8. It was shown that the main gas from the production of PET and PLA bottles was carbon dioxide. In terms of these environmental impacts, the dominance of the final stages of bottle formation is evident. Based on the detailed life cycle analysis, factors determining gas emissions were determined. In the bottle shaping process, the highest gas emission rate was recorded for bottles made of biodegradable material, while the lower for PET bottles.

Table 3. Results of studies on carbon dioxide emissions into the environment in the supply of raw material

Emission factor	PET preforms	PLA preforms
CO ₂ (kg)	0	0.004041007
SO _x (kg)	1.94397E-09	1.67815E-09
NO _x (kg)	0.000211559	0.000207507
NH ₃ (kg)	2.17501E-06	6.87151E-05
SO ₂ (kg)	0.000310567	0.000313509
CO (kg)	7.73792E-06	9.12021E-06

Table 4. Results of studies on carbon dioxide emissions into the environment in the preform heating in the shaping process of beverage bottles

Emission factor	PET preforms	PLA preforms
CO ₂ (kg)	4.83942E-09	0.005400595
SO _x (kg)	1.96541E-09	1.70588E-09
NO _x (kg)	0.000232498	0.000229347
NH ₃ (kg)	2.46021E-06	6.93443E-05
SO ₂ (kg)	0.000364713	0.000369093
CO (kg)	9.09842E-06	1.05227E-05

Table 5. Results of studies on carbon dioxide emissions into the environment in the stretching and lengthening the preform in the shaping process of beverage bottles

Emission factor	PET preforms	PLA preforms
CO ₂ (kg)	4.83942E-09	0.006414
SO _x (kg)	1.97774E-09	1.72E-09
NO _x (kg)	0.000245788	0.000245
NH ₃ (kg)	2.64164E-06	6.96E-05
SO ₂ (kg)	0.000399228	0.00041
CO (kg)	9.96541E-06	1.15E-05

Table 6. Results of studies on carbon dioxide emissions into the environment in the pressure-developed preform in the shaping process of beverage bottles

Emission factor	PET preforms	PLA preforms
CO ₂ (kg)	4.84427E-09	0.007265668
SO _x (kg)	1.98967E-09	1.73771E-09
NO _x (kg)	0.000256736	0.000258749
NH ₃ (kg)	2.79039E-06	6.9946E-05
SO ₂ (kg)	0.000427419	0.000444764
CO (kg)	1.06735E-05	1.24273E-05

Table 7. Results of studies on carbon dioxide emissions into the environment in the degassing the shaped bottle in the shaping process of beverage bottles

Emission factor	PET preforms	PLA preforms
CO ₂ (kg)	4.84427E-09	0.007404406
SO _x (kg)	1.99125E-09	1.73971E-09
NO _x (kg)	0.000258437	0.000260903
NH ₃ (kg)	2.81361E-06	6.99754E-05
SO ₂ (kg)	0.000431837	0.000450359
CO (kg)	1.07845E-05	1.25678E-05

Table 8. Results of studies on carbon dioxide emissions into the environment in the cooling the shaped bottle in the shaping process of beverage bottles

Emission factor	PET preforms	PLA preforms
CO ₂ (kg)	0.000438617	0.007617014
SO _x (kg)	2.02224E-09	1.77145E-09
NO _x (kg)	0.000261975	0.000265092
NH ₃ (kg)	2.86798E-06	7.00386E-05
SO ₂ (kg)	4.84427E-09	0.000458817
CO (kg)	1.11087E-05	1.29349E-05

As a result of the research, an attempt was made to estimate the amount of emissions of compounds into the environment. In the case of shaping bottles made of polyethylene terephthalate, the highest value of carbon dioxide emission was obtained for the cooling process 0.000438617 kg CO₂eq/1000 pieces of shaped bottles, Figure 3. A slightly higher emission was recorded for a bottle made of polylactide obtaining the value of CO₂ emitted at 0.007617014 kg CO₂eq/1000 pieces of shaped bottles, Figure 3. For the production of bottles made from polyethylene terephthalate the emission of

nitrogen oxides increased for all operations of the bottle shaping process, with the lowest emission value recorded for the heating process 0.000211559 kg NO_x/1000 pieces of preforms, while the highest for the cooling process 0.000261975 kg NO_x/1000 pieces of bottles. When analyzing the process of shaping a bottle made from refurbished sources, no increased emission of nitrogen oxides was observed, and their share in the air was about 0.000265092 kg NO_x /1000 bottles.

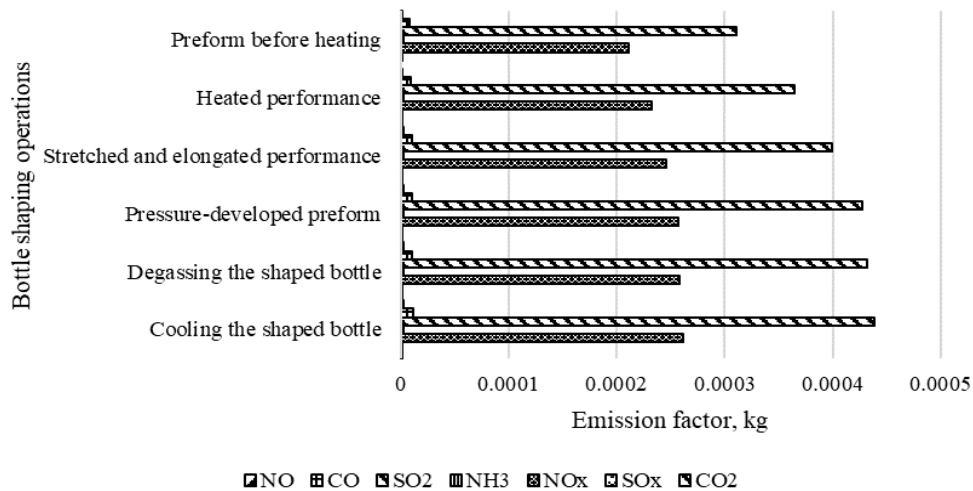


Figure 3. Emission of compounds in the process of forming PET bottles

In order to prepare a comparative analysis of CO₂ emissions to the natural environment, it was noticed that the largest amount of gas emissions was recorded for the cooling operation of a shaped PET bottle, which is largely related to the conditions of the process and the additional cooling factor, which is water. Analyzing the course of the biodegradable bottle shaping process, the largest CO₂ emissions were recorded for the degassing process of a shaped bottle. This value is determined by the conditions under which the polylactide plasticization process is carried out. The increased power of the degassing process justifies the need to provide more electricity and more compressed air Figure 4.

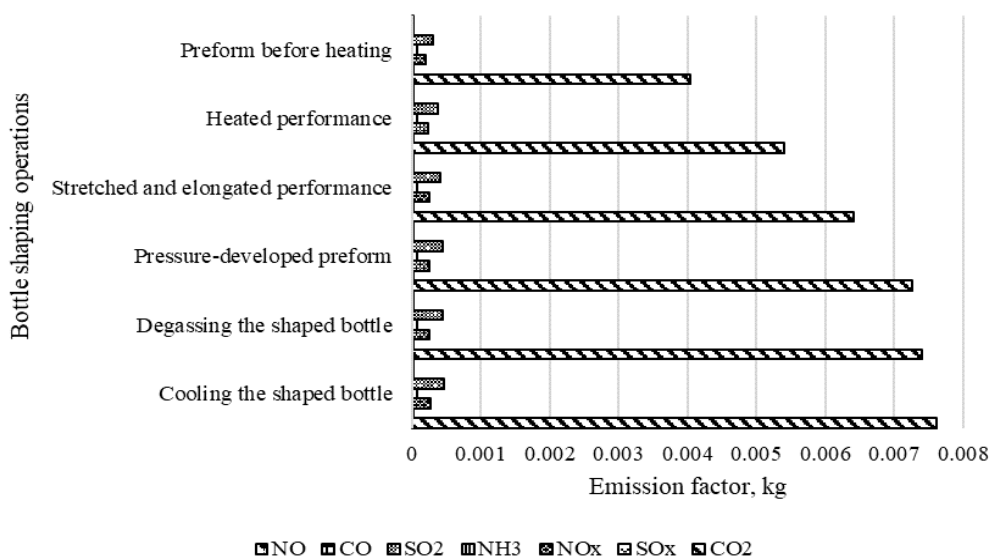


Figure 4. Emission of compounds in the process of forming PLA bottles

4. Conclusions

The main objective of the research was to determine the impact of environmental damage resulting from selected operations carried out for the process of shaping disposable bottles for beverages made of biodegradable and non-biodegradable plastics.

The most environmentally friendly was the operation of stretching and lengthening the preform made from the PLA preform. Nevertheless, the preforms made were also environmentally friendly from polyethylene terephthalate.

The presented results of analyzes are only a part of research conducted on food industry facilities. The selected operations selected were selected to show the possibilities of environmental analysis of machines, processes and devices in food production.

The environmental assessment of the cycle of shaping bottles for beverages allowed to state that at the stage of preform intake the gas emission rate is determined by the amount of raw material consumed, while to a lesser extent by the amount of electricity consumed. At the stage of heating and pre-blowing, the emission factor is associated with the source of infrared radiation used to sufficiently heat the preform and used in the process of shaping the amount of compressed air. At the stage of degassing and cooling of the finished product, the gas emission indicator is determined by the media used in the process necessary for the proper course of the process of shaping beverage bottles.

The LCA results showed that both the bottle made of biodegradable material and the bottle coming from non-renewable sources pose a real threat to the natural environment.

It is recommended to carry out further research on the production of bottles made of combined PLA and PET materials from recycling to determine whether a more sustainable PET bottle could be produced if the recycled PET resin and ordinary PET resin were mixed in specific quantities. The conclusion is uncertain because the system boundaries adopted at work have reduced the amount of environmental burdens. As a result, future research should focus on: 1) improving the availability and reliability of LCA data; 2) developing more detailed scenarios of environmental impacts and damages; 3) determining the indicators for arising deficiencies in the production process; 4) inclusion of economic analyzes in order to create a more solid and comprehensive, balanced portfolio for bottles made from biodegradable and non-biodegradable raw materials.

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