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IMPLEMENTATION OF MODERN FILMS IN THE PROCESS OF MASS PACKAGING OF BOTTLES BASED ON THE CIRCULAR ECONOMY

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Purpose: The aim of the article is to analyze the harmfulness of the process of mass packaging of bottles depending on the heat-shrinkable film used in the process and the source of electricity supply.
Design/methodology/approach: To achieve the main objective of the article, LCA analysis, gate-to-gate, was conducted within the specified system boundaries and a functional unit was adopted. The analysis was conducted in SimaPro software, using the ReCiPe 2016 method, which allows for the assessment of impacts by classifying and characterizing emissions and resource consumption based on the impact on human health, ecosystem and resources.
Findings: The research has shown that within the accepted limits of the studied system, the variant with the smallest potential environmental impact is the process of mass packaging using film with the addition of recyclate. Analysis of the process power source scenarios has shown that powering the process with energy obtained from wind is characterized by the least harmfulness in the three studied damage categories.
Research limitations/implications: The limitations of the study include several key aspects that may affect the results and their interpretation. Firstly, incomplete access to input data poses a challenge, as it limits the precision of the analysis and may lead to bias in assessing the environmental impact of the studied processes. Another limitation is the boundaries of the studied system, which may be insufficient to encompass all potential interactions and influences beyond the directly studied process.
Practical implications: The obtained results can be used as a basis for introducing changes in the optimization of the mass packaging process of bottles to reduce its harmfulness.
Originality/value: The analysis performed doesn't focus on the entire life cycle of a specific shrink film (as was done in the studies available so far) but focuses on comparing the environmental impact of the mass packaging process of bottles depending on the type of film used. The aim of this analysis is to assess the potential environmental impact of the process using biodegradable film with the addition of recyclates compared to the process variant with traditional film.
Keywords: mass packaging process, LCA, impact on environment.
Category of the paper: research paper.

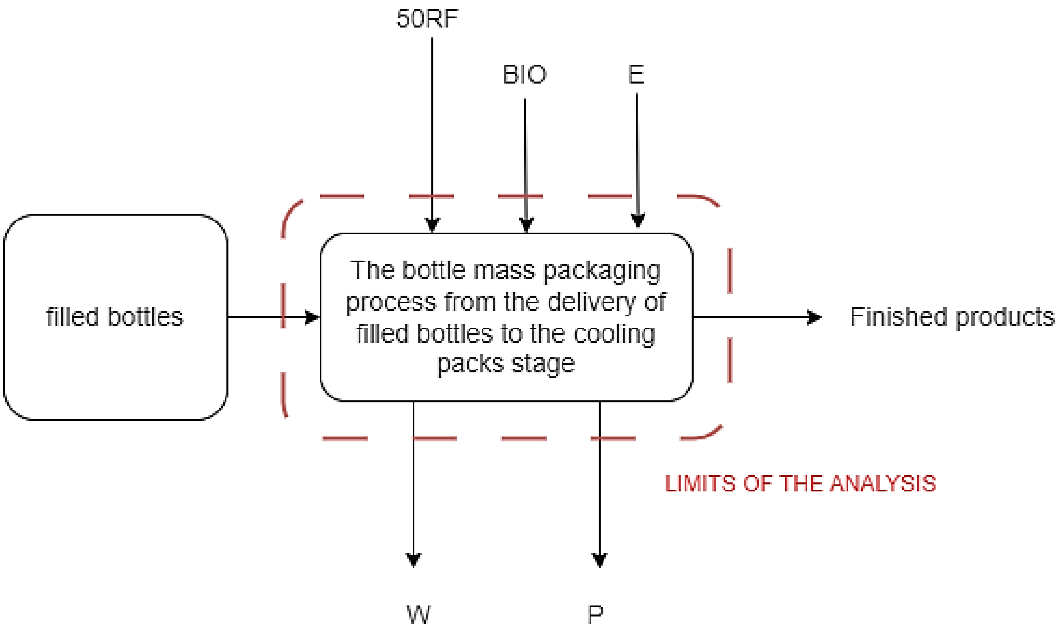
1. Introduction

The circular economy is an economic model that aims to reduce the consumption of raw materials and reduce waste generation through appropriate management, including reuse (Kirchherr J., 2017; Yang, 2023). This concept considers all phases of a product's life cycle, from design through production, use, and disposal. Striving to reuse waste is essential. The main advantages of implementing this model include reducing waste and limiting the emission of harmful pollutant (Sikorska, 2021; Nikolaou, 2021). Due to this fact, the film packaging industry is struggling with enormous pressure to adapt to prevailing trends. The use of plastics in packaging accounts for as much as 40% of their total use (Torres-Giner, 2023). Traditional films made of plastics are durable, flexible and highly resistant to external factors (Jordan, 2016). They enable safe and durable transport of products, including food. However, their wide use is also associated with a large amount of film waste, which after use requires appropriate management to reduce the harmful impact on the environment (Zeilerbauer, 2024). Alternative solutions to plastic films are appearing on the market, e.g. biodegradable films. They are produced from renewable sources and often have similar functional properties to conventional plastic films, e.g. polyethylene (Pirsa, 2020; Kibirkštis, 2022). The main products of biodegradable plastics decomposition are water, carbon dioxide, inorganic compounds or biomass. In the case of such a solution, there is no accumulation of waste, which can be a solution with a potentially less negative impact on the environment (Swetha, 2023; Flury, 2021).

In order to determine the potential impact on the environment, a life cycle analysis (LCA) is used, which can provide a comprehensive assessment of the impact of the studied object on the environment at all stages of its life cycle (Walichnowska, 2023). De Sadeleer et al. (de Sadeleer, 2024) compared the environmental impact of non-biodegradable mulch film with biodegradable ones in Nordic conditions using LCA. The authors showed that in the conditions studied, the use of non-biodegradable materials leads to lower negative environmental impacts in the whole life cycle. Vidal et al. (Vidal, 2007) compared the environmental impact of a new biodegradable film made of modified starch and polylactic acid with a conventional film. The studies showed a lower negative environmental impact for biodegradable films. Bala et al. (Bala, 2022) compared the environmental impact of using biodegradable poly-lactic acid bags, pure and reinforced with nanolays, in comparison to conventional alternatives made of polyethylene and polypropylene. The authors showed that polylactic acid film reinforced with nanoclays can be an alternative to conventional polymers in terms of mitigating climate change and reducing the use of fossil resources. Choi et al. (Choi, 2018) compared the carbon footprint generated by packaging films based on LDPE, PLA and PLA/PBAT blends depending on the disposal scenario. The study showed that the variant with PLA with landfill film was characterized by the lowest amount of carbon dioxide emissions. In the case of the PLA/PBAT with incineration variant, the greatest harmful impact was demonstrated. Based on the results obtained, the authors indicate that incineration was the least favourable variant in terms of CO_2 emissions. Many other comparative environmental analyses of the use of biodegradable plastics with conventional ones can be found in the literature (Ingrao, 2017; Jeswani, 2023; Chitaka, 2020). These studies often show a lower negative impact on the environment for biodegradable products, but there are many doubts about biodegradability depending on environmental conditions. Chen et al. (Chen, 2016) write that choosing the right waste management scenario, such as recycling, incineration with energy recovery, can be important for minimizing the impact on the environment. The choice of the right type of material should be made based on a full life cycle analysis, considering local conditions, both environmental and infrastructural. The studies provided usually concerned the entire life cycle of biodegradable films and their comparison with traditional ones. In this article, the authors conducted a life cycle analysis within the specified limits of the examined mass packaging process system using various types of heat-shrinkable films, including biodegradable films. This analysis is a response to the search for modifications to the process of mass packaging of bottles in heat-shrinkable film to reduce its negative impact on the environment.

2. Methods

The process of mass packaging of bottles in heat-shrinkable film is associated with the appearance of film waste in the economy, therefore it is considered appropriate to undertake research on the implementation of modern films that reduce the harmfulness of the process. So far, the series of articles has considered the impact of changing the heat-shrinkable polyethylene film to film with a 50% addition of recyclate (Walichnowska, 2024) and film 100% recycled (Walichnowska, 2024) on the harmfulness of the mass packaging process. The research showed that the tested batch of film with 50% recyclate addition has similar functional properties of the film compared to the conventional solution, so it can replace traditional film in the process of mass packaging of bottles. In the case of 100% recycling film, large differences were observed between the functional properties compared to polyethylene film, therefore further considerations were proposed within the composition of such film to improve its mechanical properties. Continuing the considerations in the scope of reducing the harmfulness of the process of mass packaging of bottles, a life cycle assessment (LCA) analysis was conducted, gate to gate, comparing how changing the film to biodegradable film would affect the harmfulness of the tested process within the assumed boundaries of the tested system. The tested system included the stages from the delivery of filled bottles to the line transporting them to the heating oven, where the film is shrunk (Figure 1). The functional unit in this analyse was 1000 packs.



E – electricity in process, 50RF – used recycled film, BIO – used biodegradable film, P – pollution in the form of greenhouse gas emissions (CO_2, SO_2, SF_6, N_2O), W – waste in the form of unusable packs.

Figure 1. Diagram of the process of mass packaging of bottles including input and output data.

Source: own study.

The research was conducted using SimaPro 9.6. The LCA analysis applied the ReCiPe 2016 method, which converts various categories of environmental impact – such as greenhouse gas emissions and water consumption – into measurable units. This method distinguishes between two levels of detail: midpoint and endpoint. Endpoint indicators integrate results from the midpoint level and present the overall impact on human health, ecosystems, and resources, allowing for broader contextual interpretation.

At the beginning of the study, the input data, which consist of energy flows and the material used in the process of mass packaging of bottles, were collected and calculated. The data was organized and presented in Table 1. Data for variants A and B come from an actual facility where bottles are packed in heat-shrinkable film. Due to limited access to information on biodegradable films, the same data were assumed for variant C as for variant B. The analysis compared process variants differing in the heat-shrinkable film used. In the first variant A, traditional film (LDPE) and small amounts of recycled film were assumed, in variant B – films with 50% addition of recyclates (50RF), and in variant C biodegradable film (BIO) from polylactic acid (PLA), which is obtained from plant raw materials such as corn, sugar beets or sugar cane.

Table 1.
The amount of energy used and films in analysed variant

Parameter, unit	Variant A	Variant B	Variant C
Energy, kWh	46.10	67.81	67.81
LDPE, kg	31.53	-	-
50RF film, kg	3.83	31.57	-
BIO film, kg	-	-	31.57

Source: own study.

Additionally, a scenario analysis was conducted to examine the impact of changing the power source on the harmfulness of the mass packaging process using biodegradable film. The following scenarios were analysed:

- scenario I: energy from country's mix,
- scenario II: energy from wind farm,
- scenario III: energy from country's mix and gas to the film shrinking stage.

3. Results

The analysis examined the potential impact of the process of mass packaging of bottles on the environment, depending on the heat-shrinkable film used. The study conducted using the ReCiPe 2016 method showed that the process variant using biodegradable films (assuming the use of the same amount of film per 1000 shrink-wraps) causes a greater environmental burden in the three tested categories compared to the variant with the film with the addition of recyclates (Table 2). In the category of damage to human health and ecosystems, the highest potential impact values were determined for the variant with BIO film, while in the category of damage to resources, variant A is characterized by the highest potential impact.

Table 2.
LCA analysis results for the tested process variants

Damage category, unit	Variant A	Variant B	Variant C
Human health, DALY	1.77×10^{-4}	5.97×10^{-5}	2.79×10^{-4}
Ecosystems, species.year	7.54×10^{-7}	2.39×10^{-7}	1.24×10^{-6}
Resources, $	9.77	1.24	8.16

Source: own study.

In the next step, an analysis of the impact of changing the power source was carried out, which showed that the potentially smallest impact in the category of human health damage was shown by scenario II, in which the tested process was powered by energy obtained from renewable sources (figure 2). The largest potential impact was shown for scenario I, which is 10.2 Pt and is greater by about 47% compared to the scenario with energy obtained from wind. The scenario with the use of gas in the film welding stage is characterized by a greater potential impact by about 44% compared to scenario II.

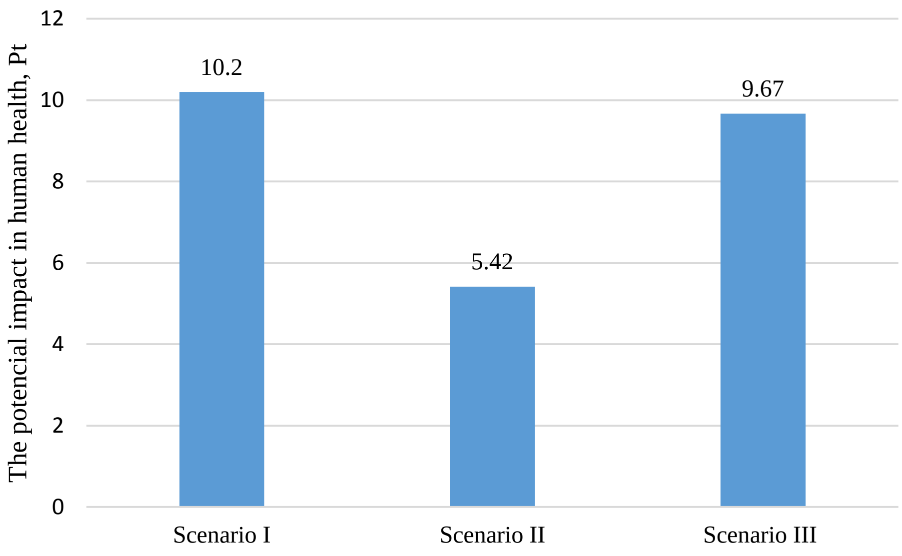


Figure 2. The impact of the mass bottle packaging process in the damage category human health, Pt.
Source: own study.

The potential impact of the studied process scenarios on the damage categories ecosystems was also demonstrated, where similarly to the human health damage category, the scenario using energy from a renewable source was characterized by the lowest potential impact on the environment at the level of 0.481 Pt (figure 3). Scenarios I and III showed similar values of the potential impact by about 35% higher compared to the process powered by wind energy.

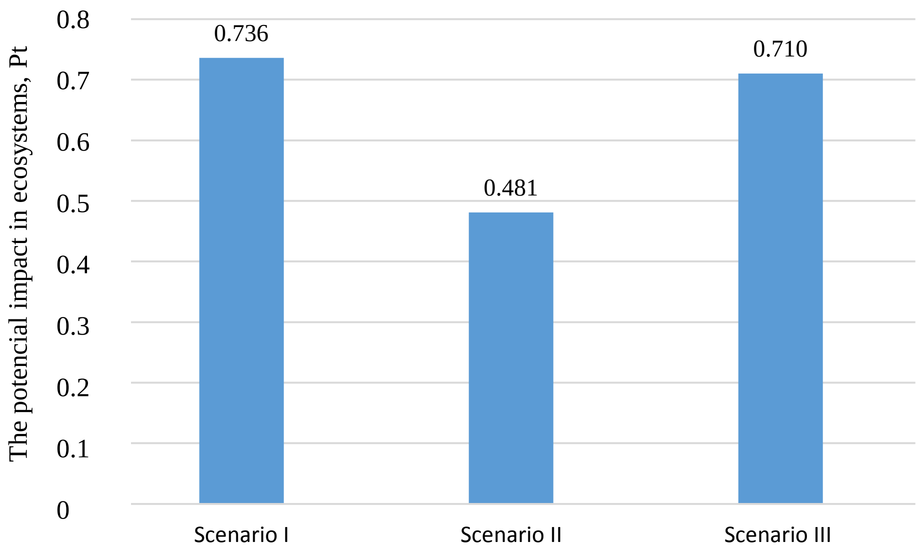


Figure 3. The impact of the mass bottle packaging process in the damage category ecosystems, Pt.
Source: own study.

In the category of damage resources the smallest potential impact on the environment was shown, similarly to the two previous categories, for scenario II of the examined mass packaging process of bottles. The potential impact in this category of damage is about 40% smaller than in the two other analysed cases. The scenario in which the process was supplied with wind energy is characterised by an impact of 3.38 Pt (figure 4).

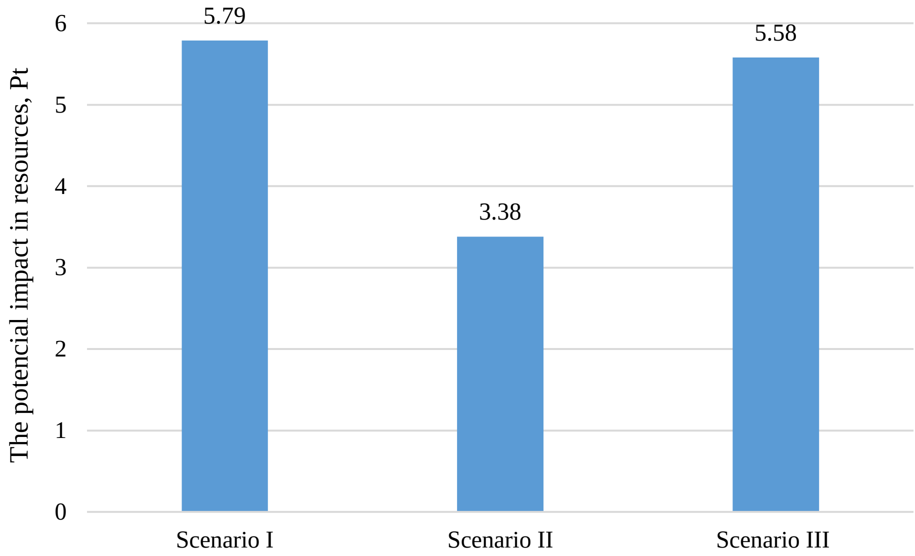


Figure 4. The impact of the mass bottle packaging process in the damage category resources, Pt.
Source: own study.

4. Discussion

The analysis carried out showed the potentially smallest environmental impact of the process variant in which recycled film was used. The use of biodegradable film in the process, compared to the use of traditional film, reduces damage only in the resources category from $9.77 to $8.16. The production process of traditional film (marked as LDPE) is associated with high consumption of non-renewable resources, including e.g. crude oil, because of which the damage within this category in the tested process variants is the highest. Biodegradable films decompose quickly, which from a general point of view is beneficial for the environment. The process may be accompanied by the formation of substances harmful to human health and ecosystems. In the literature, researchers indicate ecological problems related to the decomposition of biodegradable films (Moshood, 2022; Wu, 2021; do Val Siqueira, 2021). During decomposition, microplastics may be formed, which can penetrate ecosystems. Additionally, biodegradation carried out in uncontrolled conditions, e.g. in landfills, may cause the emission of greenhouse gases, including methane, which affects global warming. Proper and effective biodegradation of plastics requires specific conditions for industrial composting, which are a major challenge nowadays. (Narancic, 2018; Haider, 2019).

The analysis indicated a potentially lower environmental impact in the variant using recycled film. Although films of this type do not degrade, they can be reprocessed and reused multiple times. This approach aligns with global trends in sustainable development, reduces the demand for primary raw materials, and decreases the amount of waste sent to landfills. Recycling the film minimizes excessive energy consumption associated with producing primary films, thereby lowering carbon dioxide emissions and contributing to climate change mitigation. Recycled films are processed in a closed cycle, where the material is reused to create new products that retain their original functionality (Ballestar, 2022; Seier, 2023). Environmentally, they can be a more sustainable option, provided waste is managed responsibly and the recycling process is efficient (Koinig, 2022).

Technological processes are integral to the economic development of every country. The mass packaging of bottles in heat-shrinkable film, like any other process, consumes large amounts of electricity, which increases its potential environmental impact in cases of improper energy management. To reduce the negative impact of this process on the environment, it is essential to explore new energy solutions that can minimize its harmful effects (Hamed, 2022). For this purpose, an analysis of power supply scenarios for the mass bottle packaging process was carried out, which showed that powering the process with energy obtained from a wind farm reduces the harmfulness of the process in all three categories of damage, i.e. human health, ecosystems, resources.

The analysis carried out is subject to certain limitations. The analysis used input data from a specific production line, with specific operating and performance parameters. Analysing other technological lines that differ in energy efficiency and productivity, the obtained results may differ. The analysis assumed a regional boundary covering the national energy mix, based on energy produced from coal. In the case of analysing an energy mix with significant energy from renewable energy, the differences between the scenarios studied would be much smaller. In subsequent studies, it is planned to continue the considerations in the field of implementing biodegradable films in the process of mass packaging. It is planned to conduct research considering the disposal scenario in order to verify whether it has a significant impact on the training of the process using different types of films.

The LCA analysis allowed for a comprehensive inventory of input and output data in the life cycle of the process of mass packaging of bottles in heat-shrinkable film. It allowed for the identification of a variant that would contribute to reducing its negative effects on the environment. The results of the LCA analysis can be used as a tool for making decisions related to changes in energy management in each company – to reduce the harmfulness of this stage and the entire process (Rocca, 2023; Salvi, 2023). To reduce the energy consumption of the process of mass packaging of bottles in heat-shrinkable film, it is necessary to strive to increase the efficiency of individual elements of packaging machines, including mechanical systems.

5. Conclusions

The study analyses the environmental impact of the mass packaging process depending on the type of shrink films (LDPE, recycled films, biodegradable PLA films) used in the mass packaging of bottles, in accordance with the principles of the circular economy. The results showed that recycled film had the lowest negative environmental impact in key categories such as health, ecosystems, and resources, supporting the concept of closed-loop recycling. Although biodegradable film reduces resource consumption, it requires specific conditions for effective degradation and can generate microplastics if decomposed improperly. The results presented in this study indicate that:

- the use of biodegradable film in the process of mass packaging of bottles reduces damage to resources compared to the variant using traditional film;
- in all the tested variants of the process, the use of film with the addition of recyclates is characterized by the smallest potentially negative impact in the three categories of damage;
- analysis of power supply scenarios for the mass bottle packaging process showed that powering the process with energy from a wind farm reduces the potential negative impact on the environment compared to the variant with power supply from the country's energy mix by 40-47% in all three damage categories;
- the gas supply to the film shringing stage in the mass packaging process reduces damage in all three examined categories, i.e. human health, ecosystems and resources, compared to the scenario from energy country's mix;
- the obtained results are subject to certain limitations, including incomplete access to the input data;
- the limitation in the conducted analysis is the boundaries of the studied system, which may be insufficient to encompass all potential interactions and impact beyond the directly studied process. The adopted range of system boundaries may omit some important aspects of the impact on the environment, which may distort the picture of the overall impact of biodegradable films in the context of mass packaging of bottles;
- the research should be continued to reduce the harmfulness of the process through further analysis of the implementation of modern heat-shrinkable films as well as ecological power supply of the process.

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